VOLUME XXV NUMBER 5

THE

JOURNAL OF GEOLOGY

JULY-AUGUST 1917

THE LAWS OF ELASTICO-VISCOUS FLOW

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When a solid is subjected to a strain beyond the "elastic limit,"[1] its behavior may be summarized as follows:

First: The application of the stress results in a rapid elastic yield which, if inertia be negligible, is practically instantaneous. If the stress be now removed, the specimen returns to its former position.[2]

Secondly: This is followed by a slower yielding whose rate, if the stress is not too great, diminishes with time and which ultimately attains a constant value which may be zero.

If the stress be now removed, the specimen returns almost instantaneously to a point short of its original position and then

[1] The term "elastic limit" is very vague and should be replaced by limits which may be characterized as follows:

a) *The first limit* is that within which the specimen returns instantly to its original zero.

Beyond this first limit, if stress be instantly removed, the specimen promptly returns to a position short of its original one, which we may designate as the "new zero."

b) *The second limit* is that beyond which the specimen does not return to its original position or to the "new zero" even after a long time.

c) *The third limit* is that value of the stress which produces rapid yielding or rupture.

[2] In many cases the time interval between application and release of stress cannot be made sufficiently short for complete, instantaneous recovery.

continues at a much slower rate and ultimately comes to rest at a point short of its original position.

If the stress is too great, the slow yield may increase until rupture occurs.[1]

The following may be considered as a provisional attempt to formulate the behavior of substances under stress by the simplest expressions which have been found to satisfy all the essential requirements.

The formulae which follow are, in fact, sufficiently general to cover every case thus far examined, including materials of widely different properties, such as lead, tin, copper, aluminum, zinc, iron, steel, quartz, glass, calcite, limestone, slate, marble, wax, pitch, gelatin, and rubber. It may, however, be expected that a more thorough investigation will require modification in the formulae which may be made to fit special cases with greater accuracy.

The type of strain selected for this investigation is the torsion of cylindrical rods, as this is the only strain in which the form remains unaltered. It is very probable that the laws governing this special type may be made to include other distortions, such as extension, compression, bending, etc.

Very decided changes may be expected from the effects of temperature and pressure,[2] but these may be taken into account by an appropriate alteration in the value of the "constants" which enter into the formulae.

[1] Rupture may occur in consequence of such slow yielding, or it may be practically instantaneous. In the former case the result is due to separation of the viscous coupling; in the latter, to the snapping of the spring.

[2] A preliminary investigation of the effect of hydrostatic pressure on elasticity and on viscosity was begun several years ago. It was hoped that this would show results in conformity with those which maintain in the body of the earth—whose enormous pressure produces an increase in both rigidity and viscosity sufficient to make the body of the earth (which at its actual temperature under ordinary conditions would certainly be in a molten state) as solid as steel. This expectation has been partially realized for a number of materials, metallic and non-metallic, the results, notwithstanding certain anomalies—traceable to the effects of previous history—showing a perceptible increase in rigidity and a very marked increase in viscosity even with the relatively small pressures obtainable in the laboratory.

The apparatus employed for the investigation consisted of a light pulley with radius of 8 cm., over which passed two cords, the ends of which carried scale pans for holding weights.

The specimen to be investigated had a diameter of 12 mm. at the ends, while the intervening portion (75 mm. long) had a diameter of 4 mm. One end was clamped to the supporting frame and the other to the pulley, which rests on a knife-edge in the axis.

The tests consisted in measuring the angular position of the pulley by a micrometer at intervals of one minute while it is under a constant torque.

LAWS OF ELASTICO-VISCOUS FLOW

The behavior of any solid under stress may be considered as the resultant of four elements: (*a*) the elastic displacement, (*b*) the elastico-viscous displacement, (*c*) the viscous displacement, (*d*) the lost motion. These will be considered in turn.

a) *The elastic displacement.*—This is characterized by being approximately proportional to the stress and independent of time.[1] A closer approximation is given by

$$S_1 = C_1 P e^{h_1 P}.*$$

b) *The elastico-viscous displacement.*—This is manifested in a slow return when the stress is removed; and it is assumed that the same forces are brought into play during the direct motion.

[1] Doubtless there is some viscous resistance to this displacement, but it is very small compared with that of cases *b* and *c*.

* The symbols used in this discussion are:

S = displacement (twist).
P = applied torque.
F = force, stress.
C = functions of θ.
T = melting-point.
θ = temperature.
t = time.
t_0 = duration of previous strain.
E, h, k, α, P_0, a, b, m, π = constants.
e = Napierian base.

This displacement is represented by the formula

$$S_2 = A_2(1 - e^{-a\sqrt{t}}),$$

where

$$A_2 = C_2 P e^{h_2 P}.$$

c) *The viscous displacement.*—Here the elastic force is absent or very small in comparison with the viscous resistance. The specimen does not return to zero even after a long time interval.[1] The viscous displacement is given by

$$S_3 = (Ft + F_0 t_0)^\rho - (F_0 t_0)^\rho,$$

in which $F = C_3 P e^{h_3}$, and $F_0 =$ the corresponding value, when P has the value P_0 during the time t_0.

For a specimen which has not been subjected to previous strain the formula reduces to

$$S_3 = (Ft)^\rho.$$

Experiment gives $\rho = \frac{1}{2}$ approximately, until the specimen is near the rupture point, when ρ approaches the value unity.

d) *The lost motion.*—If the stress be applied for a short time (even a small fraction of a second), the specimen does not return to the original zero. The difference between the original and the new zero is the lost motion L.

It seems probable that the lost motion may be considered as a function of t such as t^r, where r is very small (less than 0.02 for zinc).

If this be considered as part of the viscous term

$$S_3 = A_3 f(t),$$

then the total viscous yield may be represented by

$$S_3 = A_3[f(t) + ct^r]$$

(if the actual stress is between the limits 0 and P_0, $c = 0$).

[1] In some cases it may be made to return to the original position by heating or by alternation (alternate positive and negative diminishing stresses).

THE RETURN

If after a time t_0 the displacement has reached the value S and the stress is released, the specimen promptly returns to a displacement short of zero and continues much more slowly in the same direction.

If the elastico-viscous displacement at the time t_0 is given by

$$S_2 = A_2(1 - e^{-a\sqrt{t_0}}),$$

the corresponding return displacement at the time t, counted from the instant of release, will be

$$R = A_2 e^{-a\sqrt{t}}(1 - e^{-a\sqrt{t_0}}).$$

To account for the viscous term, assume

$$F = \epsilon S^n \dot{S}$$

whence

$$S_3 = \left[\frac{1}{\rho\epsilon}\int F dt\right]^\rho \qquad \rho = \frac{1}{m+1}.^*$$

If F = constant, and F_0 = the constant value of F during the preceding stress during the time t_0,

$$S_3 = \frac{1}{\rho\epsilon}[(Ft + F_0 t_0)^\rho - (F_0 t_0)^\rho],$$

counting from the actual zero.

As shown by the formula, if the previous strain be considerable, the new strain is relatively small. This strengthening by previous strain is one of the striking features of the behavior of every substance which exhibits viscous yield.

If, in this expression, F represents the actual stress, it assumes that the viscous force is proportional to the velocity, which is true for fluids; but for "solid friction" the force is independent of the velocity.

It may be assumed in the present case of internal viscosity of solids that the actual law may be between these two extremes, e.g.,

$$P = a(\dot{S}')^K,$$

* Experiment gives $\rho = \frac{1}{2}$ (0.3–0.6), which makes $n = 1$. The usual assumption, $n = 0$, gives $\rho = 1$.

in which $K<1$. This would give P^n instead of P, or, in better agreement with experiment,

$$F'=CPe^{hP}.$$

The elastico-viscous term is readily obtained by making the viscosity coefficient a function of the time.

Thus, if the restoring force be represented by aS, and the viscous resistance by $et^m\dot{S}$,* the integration gives

$$S_t=S_0\left(1-\varepsilon^{-\frac{a}{r}t^r}\right),$$

where $\alpha=\frac{a}{\epsilon}$ and $r=-m+1$.†

To determine the effect of temperature, the behavior of zinc, glass, ebonite, pitch, and wax was studied. The results, together with the preceding, may be summarized in the following formulae:

$$S=A_1+A_2T_2+A_3T_3\ddagger$$

$$A_1=C_1Pe^{h_1P} \qquad C_1=E_0+E_1e^{K_1\theta}$$

$$A_2=C_2Pe^{h_2P} \qquad C_2=E_2e^{K_2\theta}$$

$$A_3=C_3Pe^{h_3P} \qquad C_3=F=E_3\theta(T-\theta)^{-1}$$

$$T_2=1-e^{-\alpha\sqrt{t}} \qquad h=b\theta$$

$$T_3=C+\left(t+\frac{F_0}{F}t_0\right)^\rho-\left(\frac{F_0}{F}t_0\right)^\rho \qquad \rho=\rho_0+\frac{a}{1+\left(\frac{\pi}{P\theta}\right)^m}$$

* The assumptions in both viscous and elastico-viscous hypotheses make the viscosity coefficient (that is, the coefficient of $\dot{S}$) zero at the beginning of the motion and infinite at $t=\infty$, which is, of course, inadmissible. Instead of S^n and t^m we might substitute $\frac{B+S^n}{b+S^n}$ and $\frac{r+t^m}{c+t^m}$, in which $\frac{B}{b}$ and $\frac{r}{c}$ are very small; but the resulting equations are far less simple and are not appreciably more accurate in expressing the results of experiment than those here given.

† The usual assumption, $m=0$, gives $r=1$.

‡ Instead of this series coupling, the following may be substituted: The unit consists of four elements: (1), (2), and (3) are in viscous contact with (4); (1) and (2) are in elastic coupling; and, finally, (3) of this unit is connected with (1) of the next following unit by an elastic coupling. The resulting formulae, however, are not essentially different from those here given.

THE PHYLOGENY AND CLASSIFICATION OF REPTILES

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Not many years ago it was the fashion to construct phylogenetic trees, often of wonderful design, for almost every group of animal and vegetable life. Because of the failure of so many of them, the practice has somewhat fallen into desuetude in recent years, and it is only hesitatingly that I have ventured, for the first time, to express in tabular form my own views of the phylogeny and classification of the reptiles. I do so the more readily, however, as I have no startling novelties to offer.

Phylogenetic schemes are always useful when constructed with proper discrimination and with due regard to the known and the unknown. They often furnish some residue of permanent knowledge, some real contribution to taxonomy and the doctrine of evolution; or, if not, by their failure they limit the field of legitimate speculation.

Especially has our greatly increased knowledge of the early land vertebrates, both at home and abroad, rendered it possible, I believe, to approximate more closely the real origin of many forms of vertebrate life than it was a dozen years ago. It was not long ago that we were seeking the beginning, or at least the early stages, of all reptile life in the order Rhynchocephalia. Because we found, or thought that we found, in *Sphenodon*, or *Hatteria*, as the genus was long called, the most generalized or primitive characters among living reptiles, it was not unnaturally assumed that its immediate ancestral stock was the most primitive reptilian type of the past. And when Credner discovered a quarter of a century ago, far back in the Permian rocks, another very primitive reptile, it was also assumed, too readily, that it was of the same stock. Upon that error, and it was an error, was built an elaborate edifice with the Rhynchocephalia as its cornerstone, until, as so

PHYLOGENY AND DISTRIBUTION OF AMPHIBIANS AND REPTILES
Devonian
Carboniferous
Mississippian
Pennsylvanian
Permian
Triassic
Jurassic
Cretaceous
Comanche
Cenozoic
Recent
Protozoa
PARAPSIDA
DIAPSIDA
SYNAPSIDA
ANAPSIDA
Squamata
BIRDS
Crocodilia
Rhyncho-cephalia
MAMMALS
Chelonia
AMPHIBIA
Dinosauria
Pterosauria
Ichthyosauria
Sauropterygia
Therapsida
Theromorpha
Cotylosauria
PROTOROSAURIA
Progonosaurus
Archosaurus
Parasuchia
CHOANICHTHYES
PSEUDOSUCHIA
PHYTOSAURIA
PELYCOSIMIA
RHYNCHOCEPHALIA
THALATTOSAURIA
PROTOROSAURIA
PLACODONTIA
DEUTEROSAURIA
ANOMODONTIA
THEROCEPHALIA
GORGONOPSIA
DICYNODONTIA
PELYCOSAURIA
EDAPHOSAURIA
PROCOLOPHONIA
DIADECTES
PANTYLUS
EUROSAURIA
EOSUCHIA
URAYUS
STEREOSPONDYLI
LABYRINTHODONTIA
LEPOSPONDYLI
LYSSOPHIA
TRIONYCHOIDEA
CRYPTODIRA
AMPHICHELYDIA
PLEURODIRA
GYMNOPHIONA
CAUDATA
SALIENTIA
North America
Elsewhere
Unknown

FIG. 1.

often in such cases, it was found that the foundation was insecure, and the edifice toppled. Everything was made to fit the uncertain base. Baur made the Proganosauria an integral part; Baur and Osborn found in the ichthyosaurs a mere wing; Broom and Osborn added a true cotylosaur; and Baur and Case built in the pelycosaurs; *Protorosaurus* and *Pleurosaurus* were mere chinks; and everybody (except Cope) united with them the lizards and snakes. I do not mention these names in any invidious spirit; they are all of men justly famous for their work in paleontology.

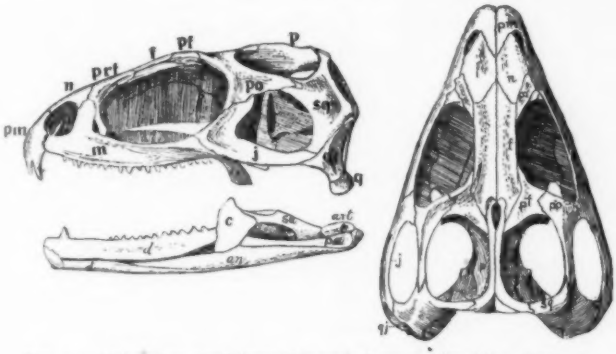

FIG. 2.—*Sphenodon*, skull from side and above. Diapsida. Recent

We all have the same proclivity, to find or to think that we find those things for which we are seeking. As Baur himself has said, they show "wie leicht man sich taüschen lassen kann, wenn man durch eine allgemeine gültige Anschauungsweise beeinflusst wird." A growing skepticism of the Rhynchocephalian affinities of *Paleohatteria* disclosed little support for the far-reaching conclusions based upon it; and, one by one, other assumptions have fallen by the wayside. A careful examination of the type specimens of *Paleohatteria* assured me that the genus was really a member of the Theromorpha. Watson holds the same opinion; and Huene has urged its relationship to the Pelycosauria.

It was Cope who, years ago, first suggested that in the temporal region of the skull the surest criteria for the classification of the Reptilia are to be found. Woodward carried the suggestion

further, and showed their availability, but it was Osborn and McGregor who first applied them definitely. They assumed too much, as we have seen, but the credit is due to Osborn, more than to anyone else, for the foundation of a true reptilian phylogeny, and to him we owe especially a better knowledge of the double-arched reptiles. He has called them the **Diapsida**, and there is no better name for them. After the elimination of the forms which we are sure do not belong with them, we are all now, I think, in accord as to their phyletic unity. It is only in details that further research (and there is much yet to be done) will be of value. The separation of the great group called the dinosaurs, first proposed by Seeley and warmly espoused of late by von Huene, into two co-ordinate divisions, the Saurischia and Ornithischia, has much to commend it. Valid arguments for the phyletic unity of the pterosaurs, crocodiles, and pseudosuchians have been offered by Huene, and their close relations with the phytosaurs and other "thecodonts" is probable. All of these have certain annectant characters, which, to me at least, are impressive. Altogether they constitute the phyletic group of the Archosauria, a term we owe to Cope.

The Diaptosauria, the other component group of the Diapsida, is much smaller than when Osborn named it; and of the few forms that are left, one, the Thalattosauria of Merriam, is discordant and uncertain. It has been offered as a connecting link between the true rhynchocephalians and the squamate reptiles; I would rather shift it bodily to the Parapsida. The Diaptosauria are the more generalized diapsids; the distinction between them and the Theromorpha is not great. The earliest assured member of the Diapsida has been carried back, I believe, no farther than late Permian, in *Youngina*, to which Broom has given the inappropriate group name of Eosuchia, inappropriate because *Eosuchus* Dollo is a true crocodile.

The origin of the Diapsida, thanks chiefly to Baur and Case, seems clear. These authors thought that the Pelycosauria were really a part of the Rhynchocephalia, and for years they were classed among them in our textbooks. It was an error, but the error has shown, definitely I think, how the Diapsida arose, by the

simple separation in reptiles with a lower temporal vacuity of the orbito-squamosal arch, leaving an upper temporal opening. The bones here are usually loosely connected, so loosely indeed in *Dimetrodon* that it is only within the past few years that we have become sure that the separation was not permanent; a permanent separation, one that would admit a knife blade even, and the deed is done. Whether or not *Ophiacodon* is a real example of this beginning, and I believe that it is, from such forms as *Mycterosaurus* the step to the diapsid type is trivial. If I am correct, and I am confident that I am, we then have the origin of the double-arched reptiles in early or middle Permian times from theromorph reptiles with a single, typically lower, temporal opening, possibly from forms not unlike *Paleohatteria*.

This group or subclass, which, with due modifications of the original concept, may properly bear the name **Synapsida** given to it by Osborn, includes scores of well-known genera of the orders Theromorpha, Therapsida, and doubtless also the Sauropterygia. It is the group that gave origin to the mammals, and has long since been extinct. In its simplest and most primitive types, together with all primitive characters of the skeleton, it has a single temporal opening bounded below by the jugal, above by the postorbital and squamosal. This opening, I believe, arose by the separation of the squamosal and jugal, and not by a definite perforation of any bone. And this opening is the sole character by which the group is ultimately distinguished from the Cotylosauria, its ancestral stock.

The evolution of the theromorph type through the dinocephalian, therocephalian, and theriodont to the mammalian seems assured by the African discoveries. In this evolution the structure of the temporal region has undergone changes of which we do not yet feel sure. The theriodont and anomodont reptiles, like the plesiosaurian, may have the temporal opening extending from the jugal to the parietal, apparently homologous with the combined openings of the diapsid forms, or, as Watson has suggested, with neither the synapsid nor diapsid; but, tracing the development as a whole, I should sooner believe that they all arose from the primitive type like that of *Dimetrodon* or *Mycterosaurus*, that is, from

a typically lower opening bounded above by the postorbito-squamosal arcade. In none of these forms does the quadratojugal enter into the opening; in some it has entirely disappeared; and the former, I believe, was the primitive condition. The opening, I believe, first appeared below and behind the orbit, at the apex of the squamosal. In the Cotylosauria the squamosal is a large bone extending far down on the side of the skull and back of the quadrate. In *Dimetrodon* and *Sphenacodon*, indeed, the quadratojugal is almost confined to the posterior side of the quadrate. Its tendency was to disappear in this type of skull, and only in some Diapsida did it become a part of the lower arch.

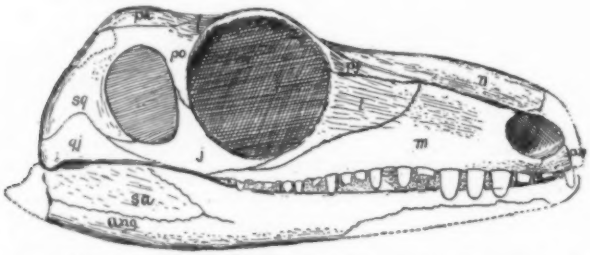

FIG. 3.—*Mycterosaurus*, skull, natural size. Synapsida, Permocarboniferous

It seems now evident that the temporal openings arose in yet another way: by the primitive separation of the postorbito-squamosal arcade from the parietal in the stegocrotaphous skull; and it seems very probable that this type of skull arose very early in geological history, as early as the lower opening, and before the separation of the upper arch in the diapsid skull. In these forms, or in most of them at least, an additional temporal bone was retained long after it was lost in other groups. And this is one of the reasons why I believe that the Ichthyosauria and the Squamata arose from a common or allied stem, direct from the Cotylosauria. For this phylum I propose the name **Parapsida.** As we have seen, Baur and others, because of the many primitive characters of the Ichthyosauria, believed that the order came from the original double-arched stem, that the lower temporal opening had been secondarily closed. Cope, in 1896, asserted that the

ichthyosaurs had an independent origin from the Cotylosauria, and so indicated in a phylogenetic diagram. Broom adopted this view in 1901. In 1904 I quoted Cope's views with approval. More recently von Huene has reached the same conclusion, finding in the Proganosauria or Mesosauria, as here accepted, either the ancestral stock or one closely allied to it. Baur, it is true, in 1887 considered the Proganosauria as the ancestral stock of the ichthyosaurs, but Baur's Proganosauria later included *Paleohatteria*, believed to be a double-arched reptile. Merriam accepted the Cotylosaurian ancestry, and Sollas very recently has voiced his approval.[1] Indeed, the opinions now seem to be unanimous and further discussion is superfluous.

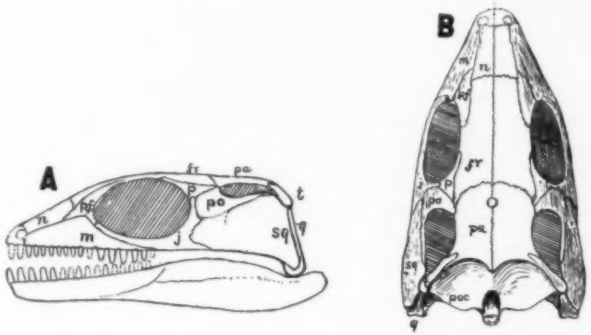

FIG. 4.—*Araeoscelis*, skull, from side (*A*), and above (*B*), natural size. Parapsida Permocarboniferous.

No order of reptiles has been the subject of more dispute than the Squamata. The apparent absence of the quadratojugal, and the presence of an additional bone in the upper temporal region, together with the freely movable quadrate, have been explained in various ways. At one time the arch articulating with the proximal end of the quadrate was considered the lower one, and the two bones the squamosal and quadratojugal. Again, the

[1] Sollas makes a rather curious error in saying that I was prepared to accept the view, with certain reservations, of the direct descent of the ichthyosaurs from the Stegocephalia. What I said was that the two bones in the temporal region of the ichthyosaurs point to a direct origin from the stegocrotaphous reptiles.

lower arch with the quadratojugal has been supposed to be lost, or replaced by a ligament, and the upper bones called by various names: supratemporal, squamosal, prosquamosal, etc. This latter view is the one now generally accepted, and, according to it, the lizards have arisen from a primitively diapsid type which, by the loss of the lower arch and the acquirement of streptostyly, has become secondarily single-arched. Twelve years ago I ventured the opinion that the two temporal bones of the squamate skull are the tabular and squamosal, the former a bone unknown or unrecognized in other reptiles since Triassic times. This view has nowhere obtained approval except by Broom. For years past von Huene, Broom, and I have repeatedly urged that the Lacertilia are a more primitive type of reptiles than the Rhynchocephalia, and, years ago, I ventured the prediction that the order would eventually be discovered in the Permian. The discovery of *Araeoscelis* in the Permocarboniferous of Texas seems to fulfil that prediction. *Araeoscelis* has a single temporal opening bounded quite as in the lizards, but with a fixed quadrate, the broad temporal region below unperforated. The cervical ribs are single-headed and attached to the centra. I am convinced that the *Araeoscelis* type of skull, by the simple emargination of the lower border of the squamosal and the consequent streptostyly, gave origin to the Lacertilia. Watson has also shown that *Pleurosaurus*, a Jurassic genus which has long been located among the Rhynchocephalia, likewise has a single, upper temporal vacuity, with a fixed quadrate, but the squamosal narrower. He believes that the genus was ancestrally related to the Squamata, though he differs from me in the interpretation of the bones of the temporal region, adopting the original Baur view of the presence of squamosal and quadratojugal. This group I have called the Protorosauria, believing that Seeley was correct in his original interpretation of *Protorosaurus*.

Whatever may be the interpretation, one thing is evident: even earlier than the origin of the upper vacuity in the Diapsida a simple upper vacuity, as in the lizards, had developed, but with the temporal region imperforate below, and this type persisted in *Pleurosaurus* to late Jurassic. If the Squamata did not originate in this way, then *Araeoscelis* and *Pleurosaurus* and probably

Protorosaurus must represent an entirely new order of reptiles, which very properly may be associated with the Ichthyosauria in the division I call the Parapsida. It might be urged that the Diapsida originated from such a type by the development of a lower vacuity after the upper one had been evolved. The arguments against this view are too many and too potent; I need not repeat them.

Admitting three chief groups of reptiles arising in late Pennsylvanian or early Permian times, we have yet another, one which by general consent is ancestral to all later amniota, the Cotylosauria, and their direct descendants the Chelonia.

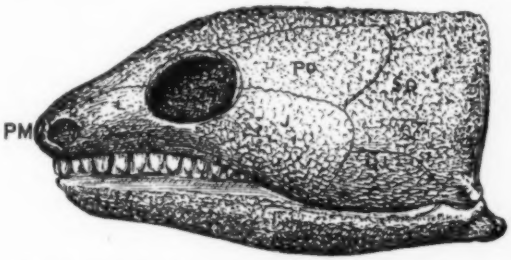

FIG. 5.—*Pantylus*, skull, from side, three-fourths natural size. Anapsida Permocarboniferous.

In this group the temporal region of the skull is wholly imperforate, and for the most part completely roofed over, a group which very properly may be called the **Anapsida**. It was Baur who first asserted that the turtles could not have originated from reptiles with a perforated temporal region. Cope derived the order directly from the Cotylosauria, through the Chelydosauria, an order based upon a misapprehension. I approved and emphasized Baur's views in 1904. Case and Hay both hold the same opinion, and only recently Watson has forcibly and convincingly presented the claims of *Eunotosaurus*, from the Permian, as a real connecting link between the two orders. And Broom and others are of the same opinion. This unanimity of opinion renders further discussion superfluous; Watson has presented the arguments.

We have, then, at least four main divisions or subclasses of the class Reptilia, all beginning in Paleozoic times, and all represented

by their direct descendants today; the birds, crocodiles, and tuatara of the Diapsida; the mammals of the Synapsida; the lizards and snakes of the Parapsida; and the turtles of the Anapsida. They suggest the following linear arrangement of the known groups, the doubtful or poorly known ones, perhaps entitled to ordinal rank, printed in italics:

Anapsida	Diapsida
Cotylosauria	Rhynchocephalia
Chelonia	*Rhynchosauria*
Synapsida	*Thalattosauria*
Theromorpha	*Choristodera*
Therapsida	Phytosauria
Sauropterygia	*Pseudosuchia*
Placodontia	Crocodilia
Parapsida	Pterosauria
Ichthyosauria	Dinosauria
Squamata	"*Eosuchia*"
Protorosauria (*Araeoscelidia*, *Acrosauria*)	

I am aware that other general phylogenetic schemes of the Reptilia have been proposed, especially by Boulenger and Goodrich, but long years of study of the reptiles has convinced me that, while all may have features worthy of consideration, the chief reliance must be placed upon the skull structure, especially that of the cranial and temporal regions. As von Huene and others have urged, these parts are the most conservative, and least liable to homoplastic duplication. Next to the skull, the ribs are conservative. In all the Archosauria the double-headed dorsal ribs are attached to the diapophyses. In the Diaptosauria (except Thalattosauria), the Synapsida (except the Sauropterygia), and Anapsida the rib tubercle articulates with the arch, the capitulum with the intercentral space, while in the Parapsida, so far as known, the ribs are attached more or less exclusively to the centra. Other characters originally proposed as distinctive between the Diapsida and the Synapsida in the wider sense have been proven to be invalid. We know that the primitive foot structure is nearly that of the lizards and *Sphenodon* of today, that the reduction of the phalanges in the theriodonts and turtles is purely homoplastic. The supposed relationship between the turtles and the plesiosaurs is also purely

homoplastic; nor am I aware of any constant character in the girdles, limbs, or ventral ribs. Goodrich, in a recent paper on the phylogeny of reptiles, relies greatly upon the structure of the feet, especially of the fifth metatarsal. I cannot accept his contentions, some reasons for which I have published elsewhere.

Just when the animals we call reptiles arose in geological history we do not know; certainly it was in early Pennsylvanian times, probably in Mississippian.' That they arose from what we call the Amphibia, forms with temnospondylous vertebrae, is certain, though there is probably not much more reason for calling the ancestral stock Amphibia than Reptilia. I prefer to call it, provisionally, Protopoda. It was ancestral to both, and both classes have advanced since their divergence, the Amphibia some, the Reptilia much. Could we find, as some time we hope that we may, in mid-Mississippian or late Devonian times, a skeleton of one of those ancestral creatures, we should perhaps not call it by the name of any known order; it would be the old question over again of the differences between animals and plants. At present we know the Protopoda only by their footprints. As it is, we are dealing chiefly with archaic forms, even by the close of Pennsylvanian times, forms which have retained in various degrees their primitive characters while adding or losing others in different ways. Just as the most primitive mammals now living have become highly specialized in the loss of teeth, so too the amphibians, as we know them in Paleozoic times, were more or less specialized or degenerated. The only known distinctive characters between the two classes, as represented by their known skeletons in Permocarboniferous times, are found in the atlas and feet, and doubtless some time we shall find these differences bridged over. For a long time we relied upon the open palate of the Amphibia, but Watson has deprived us of that support, and now we are compelled to group the characters at length in any differential diagnosis of the two classes. However, with nearly every character in common to the Amphibians and reptiles, we are never in doubt as to which class a given form belongs if we know it well enough, for all the common characters have never been found in the same specimen, and doubtless never will be in any specimen from rocks later than the Mississippian.

OUR PRESENT KNOWLEDGE OF ISOSTASY FROM GEODETIC EVIDENCE

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For a number of years investigations have been made by the Coast and Geodetic Survey upon the subject of isostasy. The first work was done under the direction of Professor John F. Hayford in connection with a study of the deflection of the vertical and the determination of the shape and size of the earth. The later work consisted of investigations of the effect of topography and isostatic compensation upon the intensity of gravity. This work was started by Professor Hayford, and the first report on it was made to the International Geodetic Association.[1] The first comprehensive report on this work was made by Professor Hayford and the writer in Special Publication No. 10 of the Coast and Geodetic Survey which appeared in 1912.[2] The investigations of gravity and isostasy were continued under the direction of the writer, and the results have been published in two reports, one appearing in 1912 and the other in 1917.[3]

As is well known, the theory of isostasy postulates that at some depth below sea-level forces are in equilibrium and, therefore, that each column of unit cross-section extending from the depth of compensation to the surface of the earth contains the same amount of matter; or, to be more exact, it may be stated that each column

[1] *Geodetic Operations in the United States, 1906–9*, a report to the sixteenth general conference of the International Geodetic Association. Separate publication of the Coast and Geodetic Survey (not numbered), 1909.

[2] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Special Publication No. 10, Coast and Geodetic Survey, 1912.

[3] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Second Paper, Special Publication No. 12, Coast and Geodetic Survey, 1912; *Investigations of Gravity and Isostasy*, Special Publication No. 40, Coast and Geodetic Survey, 1917.

of unit cross-section which extends from the depth of compensation to the sea-level surface has the same weight.

One of the main objects of the investigations made in the Coast and Geodetic Survey is to determine to what extent isostasy is proved to exist. Other objects are to determine, if possible, the method of distribution of the compensation, horizontally and vertically, with respect to each topographic feature, and to discover, if possible, the cause or causes of the gravity anomaly which cannot be accounted for by the topography and by the isostatic compensation of the topography. By topography is meant the material above sea-level on the continents and islands and the deficiency of density in the matter between the ocean surface and the bottom of the oceans.

Professor Hayford made the following statement in his second publication on the figure of the earth and isostasy. "One may properly characterize the isostatic compensation as departing, on an average, less than one-tenth from completeness or perfection. The average elevation of the United States above sea-level being about 2,500 feet, this average departure of less than one-tenth part from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet thick, on an average."[1]

Professor Hayford based his conclusion upon the fact that the mean residual or deflection of the vertical, after the isostatic correction was applied, was 2.91 seconds of arc. After only the topographic deflection was applied, the residual was 30.37 seconds. It is seen, therefore, that the application of the effect of the isostatic compensation reduced the average residual from 30.37 to 2.91 seconds.

In making the corrections for the effect of the isostatic compensation, Professor Hayford assumed that the compensation was directly under the topographic feature and that it was distributed uniformly to the depth of compensation. This depth of compensation was an unknown quantity, to be determined from the available data. The depth derived by him is 122 km.

[1] *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, special publication (not numbered) of the Coast and Geodetic Survey.

Professor Hayford stated that the anomalies or deflections of the vertical, resulting after the application of the correction for isostatic compensation as well as for the topography, would be an indication of the extent to which the conditions postulated would not be true.

Professor Hayford should have stated that the compensation departed from perfection only 10 per cent locally, for there is no indication that there is a departure of 10 per cent from the perfect state for the whole country. Some of the anomalies were positive and others negative and these tend to balance for the whole area.

Several tests were made by Professor Hayford to show the result of other methods of vertical distribution of the isostatic compensation than the one of uniformity. If the isostatic compensation is uniformly distributed through a stratum 10 miles thick, he found the most probable depth for the bottom of this stratum to be 40 miles. If the isostatic compensation is distributed with respect to depth, according to the law postulated by Professor T. C. Chamberlin, the most probable value of the limiting depth is 193 miles. The method of distribution of the compensation by Professor Chamberlin's method is given on pages 159 and 160 of *The Figure of the Earth and Isostasy from Measurements in the United States*. This is the first report[1] on the deflection of the vertical and isostasy. In regard to the Chamberlin method, Hayford said: "It is not possible to ascertain whether this compensation is more probable than the solution G compensation, uniformly distributed from the surface to a depth of 70.67 miles, since the two sets of computed deflections agree so closely that their differences are much smaller than the accidental errors."

When the investigations of gravity and isostasy were undertaken, it was concluded that the compensation should be distributed uniformly to a depth of 113.7 km., which was the depth determined by Hayford in his first investigation of the deflection of the vertical and isostasy. The uniform distribution was adopted because it made easier the preparation of the tables with which the computation of the effect of the isostatic compensation was made. It was also believed that this method of distribution was as probable

[1] Special report (not numbered) of the Coast and Geodetic Survey, 1909.

as any other simple method of distributing the isostatic compensation. It was realized by Professor Hayford and by the writer of this paper that uniform distribution to the depth of compensation could not be true at all places; yet it was thought that the departures from normal densities in the lithosphere due to the compensation were heterogeneous and that for a large area the effect would therefore be practically that of uniform deviation from normal.

What follows in this paper is largely based upon the results of the most recent investigation of gravity and isostasy (Special Publication No. 40).

In this investigation there were used 219 stations in the United States, 42 in Canada, 73 in India, and 40 other stations, principally in Europe—374 in all.

There were certain phases of the investigation which had to be confined to stations in the United States, owing to lack of data for the other stations. These consisted of tests to show whether local or regional distribution of compensation horizontally is the more probable, and also of tests to derive the most probable value of the depth of compensation based upon uniform distribution of the compensation vertically from the surface of the ground to the depth of compensation.

Three hundred and fifty-eight stations were used for the determination of the most probable values for the constants in the gravity formula which gives the value of gravity, γ_o, at sea-level for any latitude, ϕ. This formula is

$$\gamma_o = 978.039\ (1 + 0.005294 \sin^2 \phi - 0.000007 \sin^2 2\phi).$$

It is a remarkable fact that this formula agrees almost exactly with the formula derived in 1912 from only 122 stations in the United States alone. That formula was

$$\gamma_o = 978.038\ (1 + 0.005304 \sin^2 \phi - 0.000007 \sin^2 2\phi).$$

This agreement between the derived formulas is a clear indication that isostasy is present to practically the same degree in other countries as it is in the United States.

The average gravity anomaly with regard to sign for stations in the United States by the adopted method of reducing for isostasy is −0.003 dyne, while the average without regard to sign for these stations is 0.020 dyne. An anomaly is the difference between the observed and computed values of gravity. The computed value has corrections applied for the elevation of station above sea-level and for the effect of the attraction of the topography of the whole world and of the opposite effect of the isostatic compensation of the topography. The topography is considered to be that material on the continents and on islands which is above sea-level and the deficiency of material in the oceans.

An anomaly of 0.020 dyne in terms of mass is here given in order that the reader may have a clear conception of the magnitude of the deviation of the gravity from normal. If we should have a disk of material directly under a gravity station and if the disk should be of normal density, 20 km. in diameter and about 600 feet thick, the attraction on a gram mass at the station would be 0.020 dyne. An anomaly of 0.001 dyne represents the attraction of a disk of material of indefinite horizontal extent and about 30 feet in thickness on a gram mass located near the center of the surface.

The anomalies by the isostatic method varied from +0.059 at Minneapolis, Minnesota, to −0.093 dyne at Seattle, Washington. There were only ten anomalies which were greater than 0.050 dyne.

When a correction was applied to the computed value of gravity for the effect of the topography, but none for the isostatic compensation, the mean anomaly with regard to sign for the stations in the United States was −0.037 dyne. The corresponding mean without regard to sign for the stations in the United States was 0.050 dyne.

The fact that the gravity anomalies were more nearly eliminated by the isostatic method of reduction than by the methods where isostatic compensation was not considered is strong evidence in favor of the former method.

We must conclude, however, that no method can be near the truth unless it has a rather general application to different sections of the country and to different classes of topography. In order

to test the methods of reductions by this theory, the stations were arranged in five groups according to the topography. The anomalies with and without regard to sign for the several classes of topography and for the two methods of reduction—one taking into account the topography and compensation, and the other only the topography—are given in Table I. To make it easier to refer to these methods the first will be called the Hayford method and the other the Bouguer method.

TABLE I

MEAN ANOMALIES

CHARACTER OF STATIONS	NUMBER OF STATIONS	MEAN ANOMALIES			
		With Regard to Sign		Without Regard to Sign	
		Hayford; Depth, 113.7 km.	Bouguer	Hayford; Depth, 113.7 km.	Bouguer
Coast stations	27	−0.009	+0.017	0.018	0.021
Stations near coast	46	− .001	+ .004	.021	.025
Stations in interior, not in mountainous regions	88	− .001	− .028	.019	.033
Stations in mountainous regions, below general level	36	− .003	− .107	.020	.108
Stations in mountainous regions, above general level	20	+ .001	− .110	.017	.111
All stations (except the two Seattle stations)	217	− .002	− .036	.019	.049
All stations	219	−0.003	−0.037	0.020	0.050

This table shows that the Hayford reduction gives about the same values without regard to sign for each class of topography while the mean anomalies with regard to sign have a very small range if we do not consider the 27 stations at the coasts. It is probable that the coast stations are affected by the presence of Cenozoic formation, the material of which is lighter than normal. This will be referred to later. We may conclude, I think, that there is practically no relation between the sign and the size of the Hayford anomalies and the character of the topography on which the stations are located.

We find entirely different conditions in regard to the Bouguer anomalies. The size of the anomaly without regard to sign at

coast stations is 0.021, practically the same as for the Hayford method of reduction. This is, of course, due to the fact that there is very little relief in the topography at the coast. The size of the Bouguer anomaly for stations in the mountainous regions above the general level is 0.111 dyne. The range is therefore 0.090 dyne.

When we consider the mean anomaly with regard to sign for the Bouguer method of reduction, we find a range for the groups from +0.017 to −0.110 dyne. This is a total range for the groups of 0.127 dyne. If we should consider the individual stations, we should find much wider ranges for the Bouguer values than for the Hayford values. The total range for the Hayford values is from +0.059 to −0.093. The total range for the individual stations for the Bouguer reduction is from +0.057 to −0.229.

The values given above are conclusive proof that the condition of isostasy exists to a rather remarkable degree, and that the theory that the topography of the earth is not compensated for by a lack of density under the continents and by an excess of density under the oceans is far from the truth.

The fact that the country as a whole is in a high state of isostatic adjustment is evident from the values given above, but there are local deviations from normal which may be due to a number of causes. They may be due to departures from the state of perfect isostasy, to an erroneous method of distributing the compensation horizontally from the station, to an erroneous method of distributing the compensation vertically with respect to depth, to erroneous values employed for the density of the topography, or to an erroneous depth of compensation; or they may be due to the presence of material heavier or lighter than normal close to the station but below sea-level. This extra or deficient density may or may not be compensated for in lower portions of the lithosphere.

There were made, during the investigation, certain tests which throw some light upon the causes of the gravity anomalies.

It has been held by some that the compensation of topography is not distributed locally under the topographic feature, but is extended horizontally to some unknown distance. It does seem improbable that the compensation should be directly under the topographic feature and not extended horizontally to a certain

extent. At the same time, it is equally improbable that the compensation should be extended horizontally and uniformly out to any definite distance from a station. It would seem to be more probable that the compensation is distributed regionally, with the greater amount of the compensation directly under the topographic feature, and that it diminishes in amount with the distance from the feature.

A test was made to show whether local distribution or regional distribution was the more probable. The distribution in each case in the regional method was uniform. The method employed was to take the average elevation of the topography within a certain distance of the station. In one case the distance was 18.8 km., in another 58.8, in a third case 166.7 km. from the station. With the average elevation within these areas, a computation was made of the effect of the compensation, which was supposed to be uniformly distributed out to the limit of the area and also uniformly distributed from the surface to the depth of compensation.

The method of distributing the compensation horizontally necessarily leads to some error, for, as a matter of fact, the compensation of each topographic feature should be distributed regionally with respect to that particular feature. But such computations would be extremely laborious and it is believed that the results would not be materially different from those which were obtained. That erroneous results might be obtained for a single station is readily perceived when we consider that the station may be on a plain or plateau, say 167 km. in radius, and that just outside of this area there are massive mountain masses. According to the theory of regional distribution of the compensation, the compensation of the mountain masses should be extended under the plains; it should therefore have an effect on the computed gravity at the station. It would tend to make the computed value of gravity at the station smaller than it would otherwise be. On the other hand, we might have a station in a mountain mass of, say, 167 km. in radius, with plains surrounding the mass. In this case all the compensation of the mountain mass would be used in the computation of the corrections to gravity. Some of the compensation should be distributed for a distance of 167 km. out into the plains.

There were 124 stations in the United States which were used in the investigation of the regional distribution of compensation. We shall speak of the three regional distributions as Zones K, M, and O,[1] since the distances given above are the outer limits of those zones. The anomalies for the local and for the three regional distributions of compensation are shown in Table II for the 124 stations.

The values in this table give no evidence whatever in favor of any one method of distribution over the others. This is probably as it should be, for most of the stations considered were in topography of low relief. When a station is on a plateau or a plain, it

TABLE II

	Anomalies			
	Local	Regional		
		Zone K	Zone M	Zone O
Mean with regard to sign	−0.002	−0.001	−0.001	−0.002
Mean without regard to sign	0.020	0.019	0.020	0.020

is evident that the method of distribution of the compensation has very little effect on the anomaly. If the topography were of exactly the same elevation throughout the zone, the local and regional distribution of compensation would give absolutely the same value. The difference in the effect would increase with the increase in the difference in elevation of the topography in different parts of the zone. While some of the stations might have larger anomalies by some one of the methods than by the others, there would be other stations for which the reverse would be true, and the mean anomaly for all the stations by each method would necessarily tend to be the same.

We may assume, as was done when considering the relation of the anomaly to the topography, that that method of distribution is most nearly the truth which has the smallest variation in anomaly for different classes of topography.

[1] This refers to the zones used in computing the effect of topography and compensation. See Special Publication No. 10.

The 124 stations under consideration were arranged in five groups, depending upon the topography. The anomalies with and without regard to sign for the local and the three regional distributions of the compensation are shown in Table III.

The mean anomaly with and without regard to sign for the several groups and for the various methods of distributing the

TABLE III

LOCAL AND REGIONAL ANOMALIES

	Local Compensation Anomalies	Regional Compensation Anomalies		
		Zone K	Zone M	Zone O
FOR 18 COAST STATIONS				
Mean with regard to sign	−0.004	−0.004	−0.004	−0.006
Mean without regard to sign	0.018	0.018	0.018	0.020
FOR 25 STATIONS NEAR THE COAST				
Mean with regard to sign	−0.002	−0.001	−0.001	−0.001
Mean without regard to sign	0.022	0.021	0.021	0.022
FOR 39 STATIONS IN THE INTERIOR, NOT IN MOUNTAINOUS REGIONS				
Mean with regard to sign	+0.001	+0.002	+0.002	+0.003
Mean without regard to sign	0.017	0.018	0.018	0.017
FOR 22 STATIONS, IN MOUNTAINOUS REGIONS, BELOW THE GENERAL LEVEL				
Mean with regard to sign	0.000	+0.001	+0.003	+0.006
Mean without regard to sign	0.017	0.017	0.018	0.019
FOR 18 STATIONS, IN MOUNTAINOUS REGIONS, ABOVE THE GENERAL LEVEL				
Mean with regard to sign	+0.003	+0.003	0.000	−0.010
Mean without regard to sign	0.018	0.018	0.017	0.020

compensation does not throw very much light upon the question of which method is nearer the truth, although a careful analysis of the table will, it is believed, indicate that the distribution regionally to the outer limits of Zone O, 166.7 km., is not as probable as the local distribution of compensation or the regional distribution out to the limits of Zone K, 18.8 km., or Zone M,

58.8 km. The greatest range for the mean anomalies with regard to sign is for Zone O and for mountainous regions where the stations are below and above the general level. The range here is from +0.006 to −0.010, which is 0.016 in all. This range is almost as large as the average anomaly for the United States without regard to sign. The largest range for the other methods of distribution is 0.007.

We should expect the regional and local anomalies to be approximately the same for all of the stations not in mountainous regions, but we should also expect that the local and regional anomalies would differ for the stations where the relief is great. Where the station is below the general level, the computed value of gravity is less because some of the compensation of the mountains is distributed closer to the station than it would be by the local distribution. Where the station is above the general level, the computed value of gravity is greater because some of the compensation of the local topography is distributed under the contiguous valleys.

We may conclude, I think, that the solution of the problem of local distribution of compensation of the topography is indeterminate to a certain degree; that is, that any one distribution is as probable as any other one, out to a distance of 59 km. from the station. It is possible and, in fact, probable that this uncertainty may extend to a distance somewhat greater than 59 km., but it is very probable that it does not extend to a distance of 167 km. from the station. This conclusion is based upon the geodetic evidence, as furnished by the gravity anomalies, and has no connection with geological evidence. Any decision as to whether one method or another is the more probable within the distance of about 60 km. should be left to the judgment of geologists. It is of course possible that, with more geodetic data available, geodesists may be able to throw additional light on this subject.

It should be remembered that when making the test for the most probable method of distributing the compensation horizontally the anomalies are treated as if they were due only to the method of distribution. As a matter of fact, they are probably due to a number of causes, and this fact has some effect on the results of the computation, but it is believed that its effect is small.

When the researches in isostasy and in the deflection of the vertical were started, it was assumed that the compensation of topography was complete, that it was distributed directly under the topographic feature, and that it was uniform with respect to depth. This method of distribution vertically and horizontally was continued in the computations connected with the researches in gravity and isostasy. The depth of compensation derived from investigations of the deflection of the vertical, which was considered to be of the greatest probability, was 122.2 km.[1]

As it is probably true that the gravity anomalies may be due to an erroneous depth of compensation, it was decided to compute a new value for the depth, based upon gravity observations alone. The results of these computations, with numerous tables, are given

TABLE IV

	Depth of Compensation in Kilometers						
	42.6	56.9	85.3	113.7	127.9	156.25	184.6
Mean anomaly with regard to sign, for all stations	+0.004	+0.003	0.000	−0.003	−0.004	−0.007	−0.010

in Special Publication No. 40, and only the results need be given in this paper. In the investigations from which were determined the most probable depths from gravity determinations, there were used only the 219 stations in the United States. It was impossible to use the gravity stations outside of the United States because of lack of detailed data.

The depth 113.7 km., the one derived in the first investigation of *The Figure of the Earth and Isostasy from Measurements in the United States*, was used in making the reductions for compensation in the investigations of gravity. With the detailed information obtained from the computations it was possible to obtain the effect of the compensation for other depths. This was done by means of certain factors.

The mean anomaly with regard to sign for all the stations is shown in Table IV. The means without regard to sign for all of

[1] See *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, p. 54.

the stations used as a single group for the various depths of compensation had a range of only 0.002 dyne from 0.020 to 0.022. Owing to the small range, it is not necessary to show the means without regard to sign in the table. The anomalies in this table have not a very wide range, and therefore there is no very strong evidence to show that any one depth among the intermediate depths is much better than the others. The evidence, such as it is, favors the depth of about 85 km.

TABLE V

ANOMALIES AT DIFFERENT DEPTHS OF COMPENSATION

Character of Topography	Number of Stations	Mean Anomalies with Regard to Sign for Depth in Kilometers						
		42.6	56.9	85.3	113.7	127.9	156.2	184.6
Coast	27	−0.002	−0.003	−0.006	−0.007	−0.008	−0.009	−0.009
Near coast	46	+ .002	+ .002	+ .001	+ .001	+ .001	+ .001	+ .001
Interior, not in mountainous regions	87	− .003	− .002	− .001	+ .001	+ .001	+ .003	+ .005
Mountainous regions, below general level	36	.000	.000	.000	− .001	− .001	− .002	− .003
Mountainous regions, above general level	20	+0.021	+0.016	+0.009	+0.003	+0.001	−0.003	−0.006

In order to get stronger evidence as to the most probable depth of compensation, the stations were divided into groups according to the topography, as was done in several other tests. The mean anomalies without regard to sign for the seven depths considered had a total range of 0.009 from 0.017 to 0.026. Each of these mean anomalies came in the group of stations in mountainous regions, above the general level. The maximum range for any other group of stations was 0.004 and that occurred in the mountainous regions where the stations are below the general level.

The means with regard to sign varied for the different depths and the different classes of topography. These means are shown in Table V.

It will be noticed that there is only one group for which there are very decided changes in the mean anomaly with regard to sign—

stations in mountainous regions, above the general level. The anomaly is +0.021 for a depth of 42.6 km. and it is −0.006 for a depth of 184.6 km.

Computations were made to obtain the most probable depth from all the gravity data for the 219 stations in the United States. Where all stations were used, the depth was found to be 67.1 km. It was realized that the stations on topography which was not in mountainous regions were not well adapted for the determination of a depth of compensation. Owing to the low character of the topography, the effect of the compensation was nearly the same regardless of the distance from the station to which it was extended. This is due to the fact that the attraction of an indefinitely extended disk containing a certain mass but of indefinite thickness will exert the same attractive force on a given mass regardless of how far from the disk the mass is placed. It is assumed, of course, that the attracted mass is over the center of the disk. We can see, therefore, that where the compensation is nearly the same in amount under a unit area for an indefinite distance around the station it would, although a number of kilometers in thickness, attract the pendulums at a station by the same amount regardless of the thickness of the disk or column of compensation.

The condition is different in the mountain regions for those stations which are above the general level, for there the topography near the station is comparatively limited in horizontal extent and the attraction of the compensation will depend upon the depth to which the compensation is extended. The closer to the station the greater of course will be the effect of the compensation and the larger will be the plus value of the anomaly observed, minus computed gravity. Where the compensation is extended to a great depth, the effect of the compensation is decreased, the computed value of gravity is necessarily larger, and the anomaly tends to be negative.

After consideration of all the facts, it was decided to determine the most probable value of the depth of compensation from gravity data by using only the stations in the mountainous regions below and above the general level. This was done and the depth resulting was 95 km.

It is interesting to note that, in the deflection of the vertical investigations, depths of compensation were determined for a number of groups, in addition to a depth for the whole country using all the stations as one group.[1] When we use the groups which are in mountainous regions and give the value of the depth of compensation derived from each group the same weight, it is found that the depth of compensation, as derived from deflections of the vertical data, for stations in mountainous regions only, is 97 km. It is rather remarkable that practically the same depth should be obtained from such widely different geodetic data. It is believed that the mean of these two values, or 96 km., is about the best value that is available at present from all geodetic data. As in other tests made during the investigation of gravity and isostasy, it was necessary to assume that all of the anomalies were due to the erroneous depth of compensation when the derivation of the most probable depth was made. This necessarily places some uncertainty in the depth of compensation, although it is believed that the uncertainty due to that cause is moderate in amount. It is probable that the best depth of compensation which will be derived from more geodetic data will be somewhere between 80 and 130 km. This, of course, is on the theory that the compensation is distributed uniformly from the surface or from sea-level to the depth of compensation.

The writer does not believe, as was stated earlier in this paper, that the compensation is distributed locally and uniformly to the depth of compensation. It is possible that the compensation may be distributed by some other method. It is probable that there is no method of distribution that is general, that is, applicable to each local area in the country. It seems to be most probable that the compensation varies from place to place and that the greater portion of the compensation may be near the surface in one place and lower down in another, or that it may be distributed throughout a considerable depth with varying amounts at different depths.

A computation was made, but the results of this do not appear in Special Publication No. 40, which showed the depth of the disk

[1] See *Supplementary Investigations in 1909 of the Figure of the Earth and Isostasy*, p. 58.

within which all of the compensation should be concentrated in order to have its attractive effect equal to the effect of the compensation uniformly distributed from the surface of the earth to a depth of 113.7 km. In other words, if all of the compensation were contracted to the disk at the particular depth, it would have the same effect as the uniform distribution.

If the compensation is distributed regionally to a distance of 10 km. from a station the disk within which all of the compensation is supposed to be concentrated must be placed 21.3 km. below the station. With regional compensation distributed to a distance of 20 km., 60 km., or 100 km. from the station, the depth of the disk becomes respectively 28.6 km., 41.2 km., or 45.5 km. If the compensation is started at sea-level instead of at the surface of the ground, each of the depths given above should be increased by about 1 km.

These depths are of particular significance, for they represent what may be called the effective center of the compensation on the basis of uniform distribution with respect to depth and with a depth of 113.7 km. This depth, as shown by certain tests, gives practically as good results as what may be called the most probable depth of 96 km. It is significant that there can be a variation in the depth of as much as 18 km. without materially affecting the anomalies.

It is reasonably certain that the effective depth as given above would be practically the same for all of the intermediate depths used in the computations to show which was the most probable depth. We may conclude, therefore, that the figures given above actually represent the effective center of the compensation, regardless of the method of distribution of the compensation. If, for instance, the compensation were considered to be confined to a zone about 20 km. in thickness, the center of that zone would have to be between 30 and 50 km. below sea-level. If the compensation is distributed according to the Chamberlin method,[1] the greater portion of the compensation would necessarily have to come within 100 km. of the surface, but there would be part of it at some distance below that depth.

[1] See *The Figure of the Earth and Isostasy from Measurements in the United States*, p. 160.

It would not be a very difficult matter to draw curves representing different methods of distribution of compensation which would have effective depths of the compensation equivalent to those shown above for uniform distribution. If we have the effective center of compensation about what it is for the uniform distribution, then, under any method of distribution of compensation, the greater portion of the compensation would be between the sea-level surface and about 100 km.

It may be concluded from a study of the gravity data and also of the deflection of the vertical data that there is no geodetic evidence which favors any particular method of vertical distribution of compensation. Anyone is therefore free to use a method of distribution which best serves his purpose or which may fit the particular theory he may hold in regard to the constitution of the earth's lithosphere. But, in order to secure results which are as accordant as those given in the latest report of the Survey, the effective depth of compensation must be between 30 and 50 km.

It was noticed early in the investigations of gravity and isostasy that there were apparently some relations between the gravity anomalies and the densities of the materials at the surface of the earth close to the station. This subject was treated briefly in Special Publications Nos. 10 and 12, which gave the results of the earlier investigations of gravity and isostasy. With the additional material available from other countries as well as from the United States for the most recent investigations of gravity and isostasy, these relations between the gravity anomaly and the surface density are shown to be stronger.

In the United States the stations on the dense rock which belongs to the pre-Cambrian formation have anomalies which tend strongly to be positive. This is an indication that under the station the material of this formation extends to a considerable depth where the gravity anomaly is large.

It was found that the stations on the pre-Cambrian formation in Canada did not have the tendency to be positive that was shown in the United States. This may be due to the extensive areas covered by this formation in Canada. As was stated above, the attraction of a disk of material of indefinite extent is independent

of the distance of the attractive mass from the disk; therefore, if we should have in Canada a station on an extensive area of pre-Cambrian formation where the material is of uniform thickness, and if this material were compensated for by a deficiency of material below it, then the compensation would have an effect which would practically counterbalance the effect of this denser material which is near the surface.

In India there are only eight stations on the pre-Cambrian formation, six of them having positive anomalies and two negative. But the mean with regard to sign of the anomalies is nearly zero. It may be possible that the small number of stations on this formation in India prevents the stations there from showing the same relation to the formation that we have in the United States. It is worthy of note that each of the areas of the pre-Cambrian formation in the United States on which stations are located is rather small in horizontal extent. If we should have a pre-Cambrian formation 10,000 feet thick under a station with a density of the rock 10 per cent above normal, and if the formation extended 10 km. in all directions from the station, the effect of the increased density would be to increase gravity by +0.029 dyne. If this extra material were completely compensated for and the compensation were distributed uniformly to a depth of about 114 km., the negative effect of the compensation would be −0.003 dyne. The resultant would be +0.026 dyne, which is about the size of the average pre-Cambrian anomaly in the United States.

It was found that the anomalies at stations on the Cenozoic formation had a tendency to be negative both in the United States and in India. There were only two stations in Canada on this formation and they were both negative. It is probable that the reasoning employed above in regard to the pre-Cambrian anomalies will apply to the Cenozoic anomalies. The density of the material of this formation is in general about 5–10 per cent less than normal, and the presence of this light material near the station should have a greater effect on the value of gravity than the compensation of this material, if any, which would be lower down in the lithosphere.

If the Cenozoic formation should be of great horizontal extent and of uniform thickness, the effect of material of this formation

would be offset almost entirely by the effect of the compensation if this lighter material were compensated for by an excess of material lower down in the lithosphere.

The mean anomaly with regard to sign for the Cenozoic stations in the United States was −0.007 dyne. In India it was −0.017 dyne. There were 31 stations in India on this formation and 20 had negative anomalies and 11 had positive ones. The positive anomaly in every case was comparatively small, the largest being 0.033 dyne. There were 10 of the negative anomalies larger than 0.032 dyne.

Since the publication of the results of the recent investigation of gravity and isostasy, data have become available in regard to a number of gravity stations established in the Pacific Coast states, during the summer of 1916. Of 13 stations established in southern California, each one has a negative anomaly, and the mean with regard to sign is −0.037. The largest one is −0.081. This is only slightly smaller than the anomaly of −0.093 at the Seattle station. Each of these stations in southern California is located on Cenozoic material.

There were 9 stations established during 1916 close to Seattle with 8 of them on the shores of Puget Sound. Eight of these stations were on Cenozoic formation, and 7 of these had negative anomalies. The mean anomaly with regard to sign for the stations in this vicinity which were established in 1916 is −0.033 dyne.

The writer does not wish to be understood as asserting that the Cenozoic or the pre-Cambrian material is the cause of the anomaly at the stations located on those formations. He does believe, however, that the abnormal density of the material of those two formations is the cause, or rather the principal cause, of the tendency of the gravity stations located on them to have anomalies of one sign. As was stated earlier in this paper, it is not possible from the data now at hand to tell whether or not the area covered by a Cenozoic or pre-Cambrian formation, where the sign of the anomaly agrees with the density of the surface material, is in isostatic adjustment. This is due to the fact that the compensation, if present, is so far from the station that its attractive effect is very small in comparison

with the effect of the deficiency in density in the materials close to the surface and under the station.

It seems probable that we may be able to predict with some accuracy a gravity anomaly on a Cenozoic or pre-Cambrian formation when we know the latitude and elevation of the point of observation and make a correction for the topography of the world and its compensation and apply a correction for the negative or positive attraction of the deficiency or excess of matter in the Cenozoic or pre-Cambrian formation. This, of course, is with the provision that the approximate depth and the horizontal extent of the material of these formations in the immediate vicinity of the station are known. It is also possible that where a station is located on a Cenozoic formation and has a positive anomaly the Cenozoic material is of slight thickness and is underlaid by pre-Cambrian or other extra dense material.

The stations in the United States on Paleozoic formations show a tendency to have negative anomalies. The mean anomaly with regard to sign is −0.009 dyne. The Mesozoic stations have a tendency to be positive with a mean anomaly with regard to sign of +0.011 dyne. There were so few stations on intrusive and effusive formations that it is believed that no definite results were obtained from a study of them. There were enough stations in the pre-Cambrian, Cenozoic, Mesozoic, and Paleozoic formations to enable one to state rather definitely that stations on any one of them have a decided tendency to have anomalies of a certain sign. There cannot, however, be any relation between the sign of the gravity anomaly and the density of the Paleozoic or the Mesozoic material, for, in general, the density of the material of those two formations is about normal.

Where the surface density is subnormal and the gravity anomaly is positive, it may be possible that there is denser material somewhat lower down in the lithosphere if the size of the anomaly is large. By large is meant somewhat above the average size of the anomaly without regard to sign. There are a number of places in the United States in which borings have disclosed the presence of crystalline rocks at varying depths below the surface where the

surface material was light in density. Dr. David White, chief geologist of the United States Geological Survey, suggested to the writer that it may be possible to predict with considerable accuracy whether or not crystalline rocks are close to the surface under a station located on surface material of light density by considering the size and sign of the anomaly.

There has been considerable confusion in regard to the opinion of Professor Hayford and the writer as to the density of material between sea-level and the depth of compensation. Some assert that we hold that the density is 2.67 for all of this material except in so far as it is modified by the compensation. As a matter of fact, neither of us has made any assumption as to the absolute density of the material between sea-level and the depth of compensation. In the investigations of isostasy it is not necessary to know the absolute density in making computations of the effect of the compensation of the topography. It is the deviations from normal densities that are given sole consideration.

A great deal of the gravity anomaly is eliminated by the application of the effect of topography and compensation, but it is certain that the remainder of the anomaly cannot be eliminated by applying the actual density of the topography in the computations. The density of 2.67 was used for all the land topography, while there are local variations in the density of material amounting to 10 per cent or more. It is, however, impossible that the true densities, if applied, could have reduced materially the average gravity anomaly. There is not enough topography to account for the gravity anomaly. It is of course probable that in many cases the anomaly would be slightly changed if a true density were used. What applies to the density of the topography will of course apply also to the density of the compensation. There is not enough compensation, however distributed, to account for most of the anomalies. As the effect of the compensation is the opposite of that of the topography, the resultant effect is smaller than the effect of the topography alone. We must conclude that no method of distributing compensation applied generally to the country or to the world will eliminate the gravity anomalies which we now have.

We must go below sea-level and below the beds of the oceans to find the cause of the anomalies. This necessarily takes the geodesist into the realm of geology, and it is there that he needs the assistance of geologists who are familiar with the geological history of the outer portions of the earth's lithosphere and of the existence of materials that deviate from normal density.

As to the process by which isostatic adjustment occurs, we must consider this largely a matter of speculation. There is no geodetic evidence on the subject. No one can say that he knows. Of many theories or opinions one is inclined to accept that which appears to be most reasonable to him.

We may summarize the contents of this paper as follows: We have sufficient geodetic data to prove that, for large areas, such as that of the United States, considered as a whole, the condition of isostasy is nearly perfect. The data also prove that the local deviations from perfect isostasy are not more than about 25 per cent on an average. If, however, we consider that the abnormally heavy or light material which is found under a number of gravity stations is compensated for by deficiencies or excesses of density lower down in the lithosphere, we may assume that the deviation locally from perfect isostasy is of the order of 10 or 15 per cent rather than of 25 per cent. The writer believes that this assumption is justified.

There is no geodetic evidence to show whether or not regional distribution out to a distance of 58.8 km. from a station is more probable than the local distribution immediately under each topographic feature. There is geodetic evidence which makes the local distribution of compensation or the distribution regionally within 58.8 km. more probable than the regional distribution out to a distance of 166.7 km. from the station. It may be possible, though the writer believes it improbable, that there is a distance between 58.8 km. and 166 km., which would give a more probable regional distribution than the distances tested.

The geodetic evidence favors about 96 km. as the depth of compensation if the compensation is assumed to be distributed uniformly between the earth's surface or sea-level and the depth of compensation. There is no geodetic evidence to show that any

one method of distribution of the compensation is more probable than other methods. It is reasonably certain that any method of distribution of compensation must have the effective depth of the compensation at a distance of from 30 to 50 km. below sea-level. By effective depth is meant such a distance below sea-level that the effect of all the compensation condensed into a thin layer at that depth would be the same as the attraction of the compensation distributed from the surface to the depth of compensation.

The absolute density of the material between the depth of compensation and the surface of the earth is not considered by the geodesist in making the corrections for the effect of compensation. It is only deviations from normal density that he considers, and it is not necessary even to know what the normal density is.

It must be concluded that the cause of the gravity anomalies is located below sea-level, and the evidence points to the probability that at least a large part of the anomaly is due to extra heavy and extra light material in the outer portions of the lithosphere which is below sea-level.

There have been found decided relations between the sign of the gravity anomalies and the geological formation. This is evidently due to the abnormally heavy and abnormally light materials in the pre-Cambrian and Cenozoic formations, respectively. There were found relations between the Paleozoic and Mesozoic formations and the sign of the gravity anomalies, but it is not evident what has caused this relationship.

There is practically no relation between the character of the topography and the sign and size of the gravity anomaly by the isostatic method of reduction. This is a very strong argument in favor of isostasy because all other methods of making gravity reductions which do not consider isostatic compensation show most decided relations between the size and sign of the anomaly and the character of the topography.

The use of gravity stations in other countries with those in the United States gave a gravity formula whose constants were practically the same as the constants of the gravity formula derived in 1912 from data at 124 stations in the United States alone. In the

1917 formula there were 358 stations used, 216 of which were in the United States.

There was not available for the foreign stations such detailed information as was available for the stations in the United States, and it was therefore not possible to utilize the foreign stations in making certain tests, but the geodetic evidence available for the foreign stations makes it practically certain that isostasy is in as nearly a perfect state in those countries as it is in the United States.

There is no geodetic evidence disclosing the process by which the isostatic adjustment takes place. This is a matter for speculation rather than proof.

The subject of isostasy is a very important one and a very broad one, and the work that has already been done is very small in comparison with what must be done in order to discover the laws of the distribution of compensation, the extent to which it is perfect, and the cause of the unexplained deflections of the vertical and the anomalies of gravity. The field is broad, and it is necessary that other scientists than geodesists should enter it. It is especially desirable that geologists and geophysicists assist in the investigation.

THE SATSOP FORMATION OF OREGON AND WASHINGTON

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The name "Satsop" was given by the writer[1] in 1915 to a deposit of stream gravels in the Chehalis valley of western Washington. The deposit was known then to extend throughout most of the length of this valley and to occur only in dissected terraces of stained and decayed gravel standing high above the valley floor. So far as then known, the Satsop formation rested unconformably on Eocene and Miocene marine sediments. Because of this relationship and because of its limitations as a valley filling, it was thought to be of Quaternary age.

Two field seasons have since been spent in the study of this formation in Washington and Oregon. It has been found in places along almost the entire Pacific coast line of Washington and along the Columbia River valley from the Pacific to the great lava plain east of the Cascade Range. It has been identified from the literature along the coast of Oregon. Its relations to the Coast Range and the Cascade Range are very different, and constitute the chief reason for the appearance of this paper.

The Satsop formation in the Chehalis valley.—The river gravels which constitute the Satsop formation of this valley exist along the lower 60 miles of its total length of 85 miles. The formation extends back up several tributary valleys, the type sections occurring in one of these, the Satsop valley. The maximum known thickness is 300 feet. The formation is composed of local materials and is stream-bedded with dip down the present drainage lines. Dissection has reduced the formation to a series of terraces, and decay has produced a residual loam on the surface of the highest

[1] J H. Bretz, "Pleistocene of Western Washington," *Bull. Geol. Soc. Am.*, XXVI (1915), 131.

terraces and given a dull red or orange color to the upper 50 feet of gravel.

The Satsop formation along the Pacific Coast of Washington.—The terrace gravels which constitute the Satsop formation of the Chehalis valley are traceable almost continuously in the cliffs along the lower part of this valley and in the bluffs of Grays Harbor to the sea-cliffs of the narrow coastal plain.

North of Grays Harbor the formation differs from that in the Chehalis valley only in containing much clay and sand, with fragments of driftwood. In places there are strata of peat or lignite several feet thick. The gravel in some exposures is a beach shingle and lies on wave-worn and mollusk-drilled Tertiary sandstone. The formation is horizontal for the most part, and such warping as does exist is very slight. The formation rests unconformably on Tertiary and older rocks. A few marine shells record the presence of the sea, and the interbedded peat tells of tidal marsh conditions in places during accumulation of the deposit. The thickness of the formation as shown in the cliff sections does not exceed 200 feet.

The shore line of Willapa Bay, south of Grays Harbor, is largely cliffed, and all of the cliffs are cut in the Satsop formation. Clay and sand predominate. Peaty strata record the presence of fresh- or brackish-water swamps during aggradation. Shells of marine mollusks, cross-bedding due to tidal currents, and beach shingle in the gravelly strata tell of deposition in marine water. One stratum of highly fossiliferous clay is traceable for several miles along the bluffs. Most of the shells in it are of oysters, many of the valves yet attached in pairs. The shell-bearing stratum rests on blue clay, which is full of molluskan borings but contains no shells. Above the shell bed is a peaty clay containing much driftwood. Stumps *in situ* and upright stems in this layer record succession of the oyster bed by a coastal marsh. In the gravelly strata are pebbles of granite, gneiss, schist, and quartzite, all but the quartzite considerably decayed. None of these materials occur in the drainage area of either the Chehalis or the Willapa River, while all of them are common in the Satsop formation of the Columbia valley. This gravel undoubtedly was brought over into

the Willapa Bay region by distributaries of the Columbia during the Satsop aggradation.

The Satsop formation in the Willapa Bay region is a little more than 75 feet in maximum exposed thickness, with the base below tide. The strata are horizontal or depart from that attitude only in gentle undulations.

The formation may be traced back up the Willapa valley into terraces of a decayed and red-stained river gravel which rests on eroded Eocene basalt and Miocene sandstone. The relation between the coastal and valley phases in the Willapa valley is the same as that in the Chehalis valley.

The Satsop formation along the coast of Oregon.—J. S. Diller[1] has described Quaternary sediments along the Oregon coast which belong clearly to the same formation as those along the coast of Washington. Diller did not name this formation and it has subsequently received but passing mention in the literature. Hence the name "Satsop" is here extended to cover that Quaternary formation of the Pacific Coast whose minimum limits reach from the Strait of Juan de Fuca north of Washington to the Coquille valley, within 80 miles of the Oregon-California line.

Exposures of the Satsop formation examined by Diller are as follows:

Ilwaco, Washington: 14 feet of gravel, sand, and clay, the top lying 30 feet above tide. Contains fresh shells of living species of mollusks. Unconformable on tilted shales of Oligocene age.

Tillamook Bay, Oregon: 20 feet of sandstone, capping a bluff of basalt 300 feet high.

Yaquina Bay, Oregon: Nye Beach: 40 feet of horizontally bedded gray sand overlying 20 feet of tilted Miocene shales. Sand contains logs, branches, and roots, some roots apparently *in situ*. Another section: 10 feet of yellow sand overlain by 5 feet of indurated gravel, this overlain by 6 feet of sand. Another section: 30 feet of Quaternary materials containing cones identified by F. H. Knowlton as of tideland spruce.

[1] J. S. Diller, "A Geological Reconnaissance in Northwestern Oregon," *U.S. Geol. Surv., 17th Ann. Rept.*, Part I, 1896.

Newport Point: Sand and gravel unconformable on Miocene shales. Clay contains a multitude of marine shells, identified by

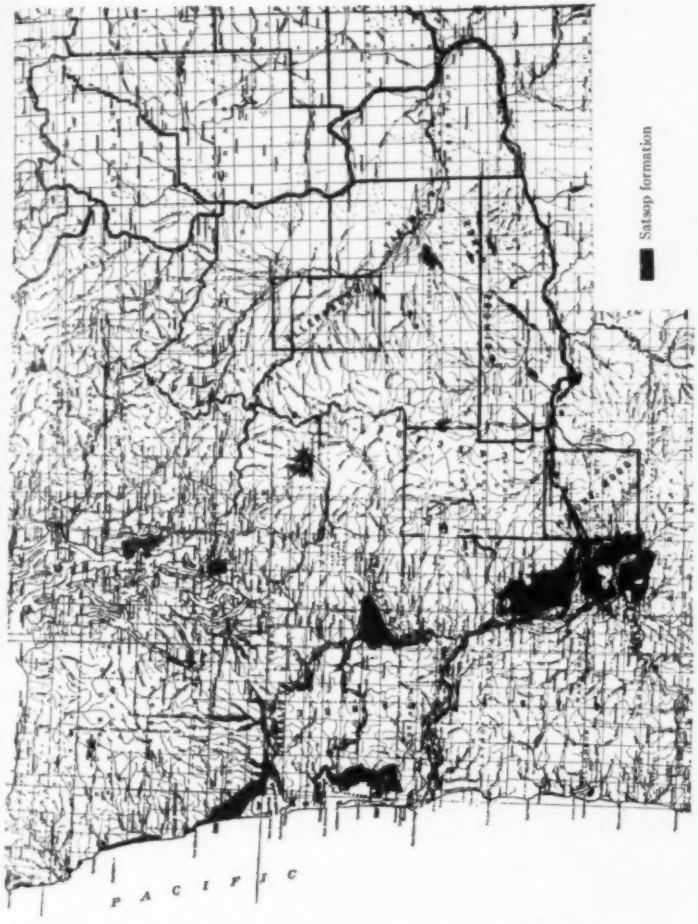

FIG. 1

Dall as belonging to six living genera. Wood and cones also present.

Coquille valley: 30 feet of sand, summit 50 feet A.T.

The Satsop formation in the Columbia valley west of the Cascade Range.—The Satsop formation in the lower Columbia valley does not differ in any essential from that in the Chehalis and Willapa valleys. It contains a surprisingly large amount of quartzite gravel. In some strata more than 50 per cent of the pebbles are of quartzite, all of which undoubtedly have come from east of the Cascade Range. Basalt, a common country rock, is also a leading constituent of the gravel. The basalt pebbles are decayed, except in the deeper portions of the deposit.

There are three large areas in the drainage of the lower Columbia where the Satsop formation covers many square miles, instead of being limited to narrow terraces. One of these areas is in the valley of the Cowlitz River, a tributary of the Columbia from the north; a second is in the valley of the Willamette River, a tributary from the south; and a third lies in a broad portion of the Columbia valley between the two areas just mentioned.

The Satsop formation in the Cowlitz valley is at least 150 feet thick. It here constitutes a broad, terraced plain and rises northward to a summit level tract about 500 feet A.T. This tract is a portion of the divide between the Cowlitz and Chehalis rivers. It bears a residual soil and with little doubt is part of the original upper surface of the formation. The pebbles in the upper 30–50 feet are softened by decay, those immediately below the soil being spaded through in excavating. At depths greater than 50 feet the pebbles are hard, but the reddish to yellowish stain penetrates as far as excavations have gone. No quartzite pebbles have been found in this part of the Satsop formation. The dissection of the tract is adjusted to a base-level recorded by a broad terrace 100 to 150 feet lower than the summit plain and about 250 feet above the present flood plain of the Cowlitz River. This terrace has been found in most of the major valleys of the region studied. From its notable development in the Cowlitz valley it is here named the Cowlitz Terrace.

Only the lower 25 miles of the Willamette valley of Oregon have been examined in the study of the Satsop formation. Most of this portion is covered by the Satsop. Numerous hills of basalt rise

through and several hundred feet above the surface of the Satsop fill. The formation is at least 600 feet thick along the Sandy River, with the base below river-level. The material is stream-bedded gravel and sand, indurated in some places to a conglomerate and sandstone. Quartzite is a common constituent for 10 miles south of the Columbia, but has not been found more than 15 miles from the master-stream. Quartzite and basalt are the most important constituents.

The Satsop formation of the lower Willamette valley is maturely dissected, the dissection adjusted to a base-level 200 feet or more above present flood plains. This level is recorded in the major valleys by a prominent terrace developed mostly in the Satsop formation but in places cut in the underlying basalt. This is the Cowlitz Terrace already described.

The uplands of this Satsop plain bear a red clay soil 10–15 feet deep. This grades down into a much-decomposed gravel. At a depth of 30 feet the pebbles are decayed only on the exterior. Below 50 feet most of the material is hard and ringing when struck with the hammer. Near the Columbia the clayey residual soil on the top of the Satsop formation contains scattered quartzite pebbles, hard, bright, polished, and apparently unaffected by the weathering which has reduced the associated basaltic pebbles to a structureless clay.

The surface of the Satsop formation in the Willamette valley lies at about 500 feet A.T. in mid-valley and rises eastward toward the Cascade Range to 1,200–1,500 feet, at these altitudes passing under the more recent lava-flows of this range. No upward slope of the Satsop surface toward the Coast Range on the western side of the Willamette valley has been found. On this side the formation terminates against hills of older basalt.

The broadened portion of the Columbia valley between the Cowlitz and the Willamette is really a continuation of the Willamette valley northward into Washington. The surface of the Satsop formation constitutes at least 200 square miles of the flat floor of this part of the valley. It is disposed in two levels, approximately 300 and 500 feet A.T., the lower of which is the Cowlitz

Terrace and the upper probably the original surface of the formation. This filling is very similar in all features noted in the preceding description to that in the Willamette valley.

Relation of the Satsop formation to the Coast Range of Oregon and Washington.—The Chehalis and Columbia rivers cross the Coast Range in capacious valleys of low gradient. In both valleys the Satsop formation has been found at closely spaced intervals from the coastal plain portion to the broad fillings east of the range. Though not continuous across the range, the character of the material of the formation, the altitudes at which it occurs, the stratigraphic relations to underlying rock and to younger gravels, and the topographic relations are such that there seems no reasonable doubt that the deposits noted in this paper are portions of the same formation.

The Cowlitz, Chehalis, Columbia, and Willamette valleys are younger than the Coast Range, and the Satsop formation is younger than the valleys in which it lies. Thus the Satsop formation was deposited after the Coast Range had been uplifted, and after its dissection was well advanced toward present maturity.

The Satsop formation along the Columbia River in the Cascade Range.—The Columbia has cut its valley across the Cascade Range down almost to sea-level. This valley is a gorge about 60 miles in length, only the western 35 miles of which have been mapped topographically. Most of the walls of the gorge are precipitous and maximum sections of 4,000 feet are available.

Numerous bluffs along the lower 12 miles of the Oregon side of the Columbia Gorge reveal a flow of gray basalt, 25–100 feet thick, in the Satsop formation. The Satsop rises northeastward in the walls of the gorge about 90 feet to the mile, bringing its base 900 feet A.T. in the salient known as Angels Rest (Fort Rock) and exposing the Columbia River lava below the Satsop. Many sections along this distance show an unconformable contact between the Satsop and the underlying basalt, and some of them show the upper 10–20 feet of this basalt to be very much decayed, far exceeding the decay of the basaltic pebbles in the lower part of the Satsop. In the section at Angels Rest the Satsop (including the intraformational lava) is 500 feet thick. A second lava-flow appears in

this section, capping the Satsop gravel and constituting the surface formation back from the edge of the Columbia Gorge. It may be traced along the cliffs to a volcanic cone known as Devils Rest, overlooking the gorge but a little back from the bluffs. Devils Rest is one of a dozen or more such cones near the gorge which have supplied the lavas overlying the Satsop formation.

The accompanying section (Fig. 2) tells the rest of the story better than would a detailed description. The intra-Satsop flow does not appear elsewhere in the range, but volcanic fragmental material is prominent in most sections of the formation. All phases of this material are present, from ash and lapilli to volcanic bombs, rudely stratified by their fall; from slightly water-rolled and poorly sorted débris to well-worn pebbles and cobbles of the gray lava, associated with equally worn pebbles of Columbia River lava and beautifully smoothed and polished pebbles of quartzite.

The Satsop deposit invariably rests on eroded Columbia River lava (a dense black basalt) and is capped by flows of gray basalt. In places the Satsop is absent and the two lava formations are in contact. The highest altitude at which the Satsop formation has been found in the Cascade Range is 3,700 feet A.T. in Benson Plateau midway across the range. Its thickness here is nearly 700 feet.

On the eastern slope of the main range the river phase of the Satsop (i.e., well-stratified gravel composed predominantly of basalt and quartzite) appears at 2,500 feet and descends eastward to 100 feet A.T. in the synclinal Hood River valley. The formation in this is

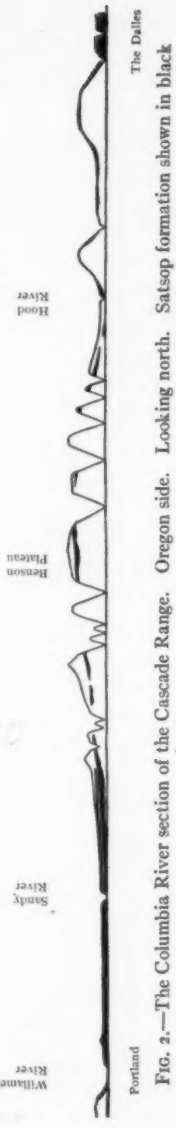

FIG. 2.—The Columbia River section of the Cascade Range. Oregon side. Looking north. Satsop formation shown in black

strikingly like that along the Sandy River, just west of the range. This is true of its composition, its structure, its degree of weathering and of cementation. It differs in having no lava-flow within the formation.

Between Hood River and The Dalles, the Columbia River has cut across two anticlinal ridges, each rising more than 2,000 feet above the stream. Each anticline is composed almost wholly of Columbia River lava. Each carries patches of a sedimentary formation composed chiefly of volcanic detritus, but containing much rounded gravel in which basalt, granite, and quartzite are present.

In the vicinity of The Dalles is a stratified deposit of volcanic agglomerate, tuff and ash, with strata of river sand and gravel, 1,000 feet thick, and capped by a flow of gray basalt. The western margin of the deposit is uptilted on the flank of the eastern anticline. Though no pebbles of quartzite or granite were found during the brief examination possible, it seems probable from stratigraphic evidence that the deposit at The Dalles is a local phase of the Satsop formation.

The Satsop formation between the Columbia and Yakima valleys.—The Simcoe Range is a prominent eastward spur of the Cascades, extending some 50 miles east of The Dalles, and separating the lower Yakima valley from the Columbia valley to the south. The range is structurally a broad anticlinal fold. Typical Satsop quartzite gravels, resting on dense black basalt and covered by gray basalt, lie in many places on the southern slope. The highest altitudes at which these gravels are known to occur in the Simcoe Range is 4,000 feet. The overlying lava does not extend far down the northern slope of the range, and the Satsop formation on this slope, unprotected by a lava cap, consists only of scattered quartzite cobbles and pebbles. All other materials in the original deposit have been destroyed by weathering. Quartzite pebbles were found as far north of the range as the southern part of the Ellensburg quadrangle. There are areas within sight of the Yakima River where these pebbles cover 50 per cent or more of the surface.

The Yakima basalt in the Ellensburg quadrangle (probably the equivalent of the Columbia River lava) is overlain by the Ellens-

burg formation, largely a sandstone of volcanic débris. Both the Yakima and Ellensburg formations have been folded into a number of east-west anticlinal ridges. Ahtanum Ridge is one of these folds in the southern part of the Ellensburg quadrangle. On this ridge the quartzite pebbles lie on the eroded edges of both the Yakima basalt and the Ellensburg sandstone. Toppenish Ridge, between the Ahtanum and Simcoe anticlines, is similarly oriented, of similar origin, and bears abundant quartzite gravel on the edges of both formations.

Relation of the Satsop formation to the Cascade Range.—It is obvious from data already presented that the outpouring of gray basalt immediately succeeded, and in part was contemporaneous with, the deposition of the Satsop formation in the Cascade Range. From the position of the Satsop formation in these mountains, it is also clear that it and the overlying lava-flows were deposited before the Cascade Range was formed.

Relation of the Satsop formation to the Methow peneplain.—Russell first advanced the hypothesis that the accordant summit levels of the Cascade Mountains in central and northern Washington record a warped and dissected peneplain. Willis and Smith[1] have named this the Methow peneplain. They have identified it on the eastern slopes of the Cascades from Lake Chelan on the north to the Yakima valley on the south. In the Ellensburg quadrangle the Methow pleneplain is thought to truncate the Ellensburg sandstone and the underlying Yakima basalt. As interpreted by Smith, these formations were gently folded before the peneplanation. Development of the peneplain brought the surface of these folds down to base-level. Renewed folding along the same axial lines is thought to have followed the truncation so that the Methow peneplain is now a warped surface lying on the tops and flanks of the anticlinal ridges.

The significant item here contributed is that the mantle of Satsop quartzite pebbles lies unconformably on the tops and flanks of at least some of these anticlinal ridges. If they constituted a stratified deposit across the eroded edges of the underlying formations, the case for planation between two epochs of folding would

[1] Bailey Willis and George Otis Smith, *U.S. Geol. Surv., Prof. Paper 19*, 1903.

be complete. However, the position of the mantle of loose pebbles is so strikingly similar to that of the stratified Satsop on the southern flank of the Simcoe Range and throughout the Cascade Range that ittle hesitation is felt in correlating the eroded surface named the "Methow peneplain" with the eroded surface beneath the Satsop formation in the Cascade Range.

But this eroded surface as exposed in the Columbia Gorge is irregular and numerous elevations in it rise several hundred feet above the base of the Satsop. This is well shown in the Willamette valley and the Hood River valley where these hills of basalt rise through the Satsop formation and the younger lavas. The surface on which the Satsop rests in the sections of the Columbia Gorge may be post-maturely eroded, but it is not a peneplain.

Further, it has been shown in this paper that the Coast Range rises above the Satsop formation in the Chehalis, Willapa, Willamette, and lower Columbia valleys and therefore was not a peneplain at the time of Satsop deposition.

The age of the Satsop formation.—Diller[1] reports that W. H. Dall found all of the species in a collection of shells from the Quaternary deposits on Yaquina Bay, Oregon, to be living forms. He also states that F. A. Lucas identified a large tooth from the same beds as that of a Pleistocene mastodon and that F. H. Knowlton identified cones from this formation as those of "*Picea stichensis* Carr.," the tideland spruce growing along this coast today.

In another paper[2] Diller has described deposits between Cape Blanco and Elk River, Oregon, about 50 miles north of the California line, which he names "Elk River beds." Dall states that the fossils collected from these beds are probably Pleistocene in age. Martin[3] has more recently examined the Cape Blanco region and reports two faunal horizons in the Elk River beds, the upper of which is very closely related to the Upper San Pedro series and "is

[1] J. S. Diller, "A Geological Reconnaissance in Northwestern Oregon," *U. S. Geol. Surv., 17th Ann. Rept.*, Part I, 1896.

[2] J. S. Diller, "The Topographic Development of the Klamath Mountains," *U.S. Geol. Surv., Bull. 196*, 1902, p. 30.

[3] Bruce Martin, "The Pliocene of Middle and Northern California," *Univ. of Cal. Publications, Bull. Dept. Geol.*, IX, No. 15 (1916).

at least Pleistocene in age" and the lower of which probably is very late Pliocene. The Elk River beds overlie the Empire beds with angular unconformity. Ralph Arnold and B. L. Clark[1] consider that the fauna of the Empire beds is "of very nearly the same age as that of the Purisima formation in the Santa Cruz Mountains of California, which is Pliocene, and not the oldest Pliocene" (Clark). The Elk River beds are apparently the same as the deposits of the Oregon coast farther north, which Diller called Quaternary.

Ralph Arnold,[2] in a description of the geology of the coast of the Olympic Peninsula of Washington, maps and names what is here called the Satsop formation as "Pleistocene gravel, sand, and clay." He notes the presence of tilted Pliocene beds (his Quinault formation), bearing a fauna similar to that of the Purisima formation of California. On these beds the Satsop formation rests with angular unconformity. B. L. Clark[3] believes that present knowledge of the Pliocene faunas of the Pacific Coast upholds Arnold's determination and that the scarcity of extinct species suggests strongly that the fauna is rather late Pliocene in age, though not the latest Pliocene.

Harold Hannibal,[4] in a paper by Ralph Arnold and himself, notes the Quaternary age of the oyster-shell bed in the Satsop formation of the Willapa Bay region.

Diller also collected fossil shells from shales 700 A.T. on the slopes of the Columbia valley 35 miles from the coast. Dall refers the shells to the Pliocene. The Satsop here is a terrace gravel down in the valley and younger than the Pliocene beds.

A clay stratum with abundant fossil leaves has been found in the Satsop formation on the western slope of the Cascade Range. Knowlton has examined collections from this bed and is of the opinion that the flora is Quaternary in age. He finds leaves of

[1] Personal communication.

[2] Ralph Arnold, "A Geological Reconnaissance of the Coast of the Olympic Peninsula, Washington," *Bull. Geol. Soc. Am.*, XVII (1906), 451.

[3] Personal communication.

[4] Arnold and Hannibal, "The Marine Tertiary Stratigraphy of the North Pacific Coast of America," *Proc. Am. Philos. Soc.*, 1913.

Quercus venustula and *Sequoia sempervirens* in the collection. Both are living species.

Age of the Cascade Mountains.—If the foregoing determinations are correct, the Cascade Range, at least in this portion, is of Quaternary age.

Acknowledgments.—During the progress of the field work on which this paper is based, nine weeks were spent with the Washington Geological Survey and four weeks with the Oregon Bureau of Mines and Geology. I wish to acknowledge indebtedness to both organizations, and in particular to Mr. Ira A. Williams, with whom I was associated during the work for the Oregon Bureau.

THE CORROSIVE ACTION OF CERTAIN BRINES IN MANITOBA[1]

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The brines geologically considered.—The Manitoban escarpment consists of a range of hills which fringes on the western side the lake system of which Cedar Lake, Red Deer Lake, Lake Winnipegosis and Lake Manitoba are the most important members, and extends southward beyond the international boundary line into North Dakota. It reaches, in the Porcupine Mountain, a maximum elevation of 2,500 feet above sea-level. At the foot of the escarpment the plain slopes gently eastward from an elevation of 900 feet to one of 700 feet. The escarpment is the eastern edge of the Cretaceous shales which extend throughout the western prairies. The shales were uplifted in early Tertiary times, and were eroded from the Red River valley back to the escarpment before the end of the Tertiary period. On this surface of erosion limestones of Paleozoic age are exposed, Ordovician, Silurian, and Devonian strata appearing successively from the edge of the pre-Cambrian shield to the escarpment; while the Dakota sandstone—the lowest member of the Cretaceous series—rests directly on the surface of the Devonian limestones. The basin of the lake system has been carved from Devonian limestones and dolomites.

At the foot of the escarpment, on the west side of the lakes, a series of salt springs emerges from middle and upper Devonian strata (the Winnipegosan dolomite and Manitoban limestone respectively).[2] These springs follow the base of the escarpment for a distance of 250 miles, but are found in greatest numbers on the west shore of Dawson Bay, at the north end of Lake

[1] Published with the permission of the Directing Geologist, Geological Survey of Canada.

[2] R. C. Wallace, "Gypsum and Brines in Manitoba," *Memoir Geol. Surv. Canada* (in press).

Winnipegosis. Around the springs are flats, absolutely devoid of vegetation, from a half-acre, as the case may be, to several hundred acres in extent. These the traveler may quite unexpectedly find in the midst of a dense forest; but the majority of the springs are to be found in close proximity to river or lake.

The brines are not confined to a single geological horizon. They appear in both the Winnipegosan dolomite and Manitoban

FIG. 1—Bowlder-strewn salt flat, Geikie's Creek, Sagemace Bay, Lake Winnepegosis

limestone, the combined thickness of which is approximately 250 feet. Owing to the comparatively level surface and the appreciable dip of the strata toward the west, the difference in elevation between the various springs is very small—not more than 50 feet. The springs may consequently be referred with greater exactness to a contour horizon than to any geological horizon.

The Dakota sandstone, which directly overlies the comparatively porous Devonian strata, is a well-known water-bearing

horizon in the middle northwestern states and in the western provinces. It is capped by impervious shales, and the water, which circulates under considerable hydrostatic pressure, apparently penetrates laterally into Devonian strata, leaches sodium chloride from certain horizons in which the salt has been precipitated with the limestone, and reaches the surface where the covering of drift is thin or absent. On an average approximately 430 gallons of brine reach the surface per minute during the dry season; and the salt, if evaporated, would cover the main salt area (200 miles by 30 miles) with a coating 2 feet thick in 10,000 years.

TABLE I

	Brine*	Sea-Water†		Brine*	Sea-Water†
K	1.37	1.11	HCO_3	0.20	.....
Na	34.99	30.59	Cl	55.95	55.29
Ca	2.02	1.20	Br	0.04	0.19
Mg	0.55	3.73	I	Nil	.....
Fe	.....	.....	Si	0.03	.....
Al	0.01	.....	Percentage salinity	7.29	3.30 to 3.74
SO_4	4.88	7.69			
CO_3	Nil	0.21			

* From Salt Creek, Salt Point Peninsula, Lake Winnipegosis. Professor M. A. Parker, analyst.
† Mean of 77 analyses by W. Dittmar.

Composition of the brines.—Numerous analyses have been made of the brines. The composition is remarkably uniform, differences occurring only when the brines pass through a considerable depth of glacial drift before reaching the surface. In this case the percentage of Ca and SO_4 ions is considerably greater than normal. Table I gives the analyses of a typical brine, Dittmar's average of 77 analyses of sea-water being given for comparison.

The analyses are given in percentages of total solids. The percentage of salinity in the analysis quoted is somewhat greater than normal, but the percentage values for the constituents vary only slightly from the figures quoted. While on the whole the brine is very similar to sea-water, it is a distinctly purer solution of sodium chloride. The relative percentages of Ca and Mg ions differ in a sense, which may be accounted for by the abstraction of Ca ions by marine organisms. The apparent differences in the carbonate

values are due to the fact that in the statement of the analysis of sea-water the total carbonate is reckoned as normal carbonate. The concentration of the brine is, however, notably higher than that of sea-water.

Action on the bowlders.—The glacial drift was to a large extent derived from the pre-Cambrian areas in the north. The bowlders which cover the bare flats where the salt springs are found are mainly gneissose or granitic, though occasionally dark-green epidiorites or Paleozoic limestones are seen. Chemical solution has taken place on an extensive scale, many bowlders having been reduced on every side by at least a foot. This is very clearly seen in the salt creeks in which the water is carried from the springs to the lake, the bowlders standing on a much-eroded base, like the rocks of a great sand desert. On the flats the bowlders are pitted into very fantastic forms, the ferromagnesian minerals having suffered to the greatest extent. Not even quartz nor garnet has escaped the action of the solvent. Gneissose structures are accentuated by differential weathering, garnetiferous bands standing out in special relief. As the corrosive power of the brine is apparently much more intense than that of sea-water, it is of interest to inquire into the processes involved in the disintegration of the rock.

Chemical processes.—Regarded as a chemical agent, the brine may be considered to be a weak solution of sodium chloride. A considerable amount of experimental work has been done on the action of solutions of sodium chloride on minerals, but the evidence is somewhat conflicting.[1] Joly has, however, proved that sodium chloride, in the presence of the atmosphere, is a more active disintegrating agent than pure water. Daubree's experiments were conducted under somewhat different conditions. In the case of the brines physical conditions have been favorable. Normally the salt crystallized in thin crusts at the base of the bowlders. The salt is somewhat deliquescent, and gradually extends upward over the side of the bowlder, till a thin coating of brine, somewhat diluted during the process, covers the whole bowlder. The conditions are thus most favorable for chemical activity in presence of the atmos-

[1] Daubree, *Synthetische Studien zur Experimentalgeologie*, 1880, 205; Thoulet, *Compt. Rendu*, CX, (1890), 652; Joly, *Proc. Roy. Irish Acad.*, XXIV (1902).

phere; and the writer believes that it is primarily as an agent for distributing the liquid in a thin film over the bowlder, and only secondarily as a direct chemical agent, that the dissolved material in the brine acts in the process of disintegrating the bowlder. It has been proved conclusively that water is itself an agent of considerable chemical power and that it acts most vigorously as a

FIG. 2.—Corroded bowlder, salt flat, Pelican Bay, Lake Winnipegosis

corrosive agent when in intimate contact with the atmosphere, as, for instance, at a water surface.

The actual process of disintegration is necessarily different for different minerals. The ferromagnesians, more particularly the amphiboles and pyroxenes, have suffered to a greater extent than the feldspars. The alkaline earths are somewhat readily attacked and dissolved as carbonates or chlorides, and silica with alumina, mixed or combined, is left in colloidal form. The percentage of soluble material in the case of the feldspars is correspondingly smaller. To some extent, with the metasilicates at least, the

process is one of hydrolysis; and while it may be effected by water alone, it is doubtless hastened by the carbon dioxide of the atmosphere. The gels which are formed during the process of decomposition are irreversible—that is, they cannot, by the action of electrolytes, pass over into sols and be in this way removed from the sphere of action. They exercise, however, a selective absorption, alkalies being removed from the brine while the acid radicals remain in solution. With potassium salts in particular this property of the colloids of the soils is of importance in retaining the valuable ingredients of fertilizers. This selective absorption tends, therefore, to hydrolyze the chloride, and to render the solution more acid. The free acid reacts on the partially decomposed minerals, causing further disintegration. Quartz is not affected thereby, but the corrosion of quartz is in all probability due to the action of alkaline carbonates.

In short, then, the principal fact in the disintegration is the intimate contact of the liquid (in a very thin film) with the atmosphere and the rock. The initial stages of the disintegration are caused by the action of water in contact with air rather than by that of salts in the water. Colloidal precipitation, which takes place when decomposition of the silicate begins, leads to selective absorption and consequent acidification of the solution, giving rise in turn to further, and probably more intense, disintegration. The process is continuous, gel being continuously precipitated, and further selective absorption taking place. The gel, being irreversible, is not taken up as an emulsion, and can consequently be removed only mechanically.

Comparison with the action of sea-water.—On comparing the action of sea-water on bowlders of similar composition to those attacked by the brines, one finds an undoubtedly real difference in the degree of corrosion. It is, however, a difference in degree, not in process. The evidences of chemical erosion caused by the sea-water are to a large extent removed by mechanical attrition caused by the impact of the waves on the bowlders, and the consequent rolling of the bowlders on the beach. Even in large bowlders, however, where rolling is reduced to a minimum, the evidence of chemical disintegration is small indeed in comparison with that of

the bowlders from the salt flats. The relatively small difference in concentration of sodium chloride is not sufficient to account for the difference in chemical activity in the two cases.

Bowlders between high and low watermark are situated similarly to those on the salt flats in one particular—they are in intimate contact with the solution and with the atmosphere. They are

FIG. 3.—Corroded bowlder, salt flat, Pelican Bay, Lake Winnipegosis

differently placed, however, in that they are alternately water-covered and dry to the base. Evaporation does not proceed so far that sodium chloride is precipitated, and films of liquid are not fed over the surface of the bowlder from the base. The initial disintegration of the bowlder is consequently less readily effected, and the acidification of the solution through absorption is to a similar extent retarded.

While to different physical conditions may be attributed the difference in degree of corrosion of beach bowlders and bowlders

of similar type in salt flats, the fact of chemical erosion by sea-water is emphasized by the study of the action of this essentially similar brine. The chemical action of sea-water on igneous rocks between high and low watermark must be much more considerable than is generally believed. The disintegration attributed to mechanical attrition is undoubtedly, in part, at least, chemical. Sea-water under great pressure is apparently a solvent for the volcanic débris which reaches the bottom of the deeper ocean; but the solvent power is intensified by contact with the atmosphere, even at ordinary pressures. Conditions are most suitable when the three phases—solid, liquid, and gas—remain in intimate contact for considerable periods of time. Such is the case where shallow pools of water are imprisoned in the hollows of the rock surfaces when the tide recedes; in these cases evidences of corrosion are very clear.

It would be futile to attempt to compare in intensity the action of sea-water on beach bowlders and that of rain-water impregnated with humus acids from the soil. Data are not available in the field. It must suffice, at this stage, to rank sea-water and acidified rain-water side by side as two potent agents from the chemical, as from the mechanical, standpoint, in the disintegration of rocks.

NOTES ON THE 1916 ERUPTION OF MAUNA LOA

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III

The writer spent the two days and night of May 30 and 31, 1916, in making a hurried reconnaissance of the Kahuku branches of the recent flow, and of the region near its source, where action was still going on, though the eruption already had greatly diminished. There had been no forward movement of the flows at their fronts later than May 27 or May 28. A preliminary account of this work was published at once in the *Weekly Bulletin* of the Hawaiian Volcano Observatory.[1] However, difficult foot traveling was encountered, and somewhat adverse weather conditions, which prevented thorough and accurate work; and the presence of fog and fumes led to erroneous estimates of distances and heights; also, our guide applied place-names incorrectly and his errors naturally found place in the early report. Further, observations of much interest, but not pertinent to the present subject, were included in that account. Hence an abridged and corrected statement relating to the 1916 action finds appropriate place here. Much that was only glimpsed on this hurried trip was fully confirmed by the later study. Whence certain observations thus confirmed it is convenient to mention here.

ITINERARY

The writer and one companion left the observatory in the early evening of May 29 and motored to the village of Waiohinu, where the night was spent. Early the next morning we motored to a gate of the Kahuku ranch about a mile west of the ranch buildings. Here we were joined by the guide, and the party set out on horseback at 8:00 A.M., going up the south slope of the mountain between

[1] Vol. IV, 6, pp. 51–57.

the flows of 1868 and 1887. At 10:30 A.M. we reached the southernmost "toe" of the front of the Kahuku branch of the 1916 flow. Here we turned off to the right to pass around this flow and up on the east and north of it. We followed an upland trail toward Kapapala until we came into a *Kipuka*, a long, narrow strip of forest land extending up the mountain between two barren streams of *a–a*, known by the name Kipuka Akala. At the lower end of this we left our horses. We reached it shortly before noon, and at noon we set out on foot up the mountain, taking a northwest course toward the general source of the new flow, north of the conspicuous cluster of cinder cones marked Puu o Keokeo on the government map. (There is dispute as to whether this name is correctly applied to this group of cones, but there is no doubt that the members of the group so mapped were those identified.)

As we planned to spend the night near the source we were necessarily laden with food, water, photographic equipment, etc., and blankets or extra clothing—a moderate load for each man. For about an hour we made our way upward alongside the strip of forest, but walking in the open chiefly over old *a–a*. At about 1:00 P.M. we came out onto a barren, complex network of *a–a* flows of varying direction and age—much of this apparently of 1907 date—and over this very difficult surface we clambered until a little after 5:00 P.M. We then had reached an old cinder cone situated between two and three miles from Puu o Keokeo in a direction a trifle east of north. This cone was about a quarter of a mile east from the rift-line source of the 1916 flow described below. We had not reached the upper limit of this source, which had been our goal, but it became impracticable to go on farther. Here we stationed ourselves in the lee of this old cinder cone and passed the night, practically all of which the writer devoted to observation of the action and conditions along the visible length of the rift source.

At 4:50 A.M. on May 31 we began the descent. At 9:40 A.M. the horses were reached, and at 10:15 A.M. we started on our way to Puu o Keokeo, going around the southern end of the Kahuku branches of the flow and up on the western side of them. By noon we reached a flat clearing, where we dropped our camp equipment

and immediately proceeded upward on horseback to a point very near to Puu o Keokeo, on a low ridge of ancient pahoehoe which extends a short distance eastward from the conspicuous cluster of cinder cones. In clear weather this slight eminence affords an expansive view to northward, and much wider views can be obtained from the summits of the cones near by. On this occasion we obtained only partial views through driving fog and clouds, and in brief clear spells between small local showers. We reached this point of outlook at 2:20 P.M. It was impracticable to keep horses here overnight, and unnecessarily uncomfortable to remain ourselves without camp equipment in such unsettled weather, especially as our hasty reconnaissance was completed, so we began our descent at 2:35 P.M., and returned on horseback to Waiohinu, which we reached at 8:30 P.M. We returned to the observatory the next day.

Thus we passed completely around the Kahuku branches of the new flow, except for their breadth near the source. In this way, especially on the foot journey, and also from the ridge near Puu o Keokeo, a good general survey was obtained of conditions along these and near their source; and in limited localities, particularly those encountered on foot along the eastern side of them, many matters of detail were observed. Conditions of the traveling, distance, and weather prevented examination of the upper limits of the source, of the action and conditions on the sides toward Kona, and the making of photographic records.

GEOGRAPHICAL NOTES

The closely grouped cluster of old cinder cones, named Puu o Keokeo on the government map, of which the highest point is 6,870 feet above sea-level, forms a low but conspicuous landmark on the south-southwest flank of Mauna Loa. Extending east-southeastward from this for a half-mile or less is a low ridge of ancient pahoehoe rising from 30 to 50 feet above the surrounding country.

A long narrow belt marked and characterized by many cinder cones (double semicones built by spatter outfall on both sides of open rift cracks in parallel linear arrangements) leads upward in a

practically straight line from a point a little west of this conspicuous group to the summit plateau of Mauna Loa (see the photographs, Plate VI, *a* and *b*). North of this lava ridge and east of the belt of cinder cones (and to a less extent west of it also) is a comparatively flat area. For a considerable distance to the northward toward the summit, the surface of this stands at a lower altitude than the summit of Puu o Keokeo, and its eastward extension from the belt of cones, though variable, has a width of from two to three miles. This makes a very conspicuous upland flat of very slight grade on a broad dome surface which is itself of very gentle slope. South of Puu o Keokeo the usual slope of the mountain is resumed. At the southeast and east this broad, irregular flat passes imperceptibly into the irregular, broken slope of the dome. Several miles to the north of Puu o Keokeo the flat passes rather quickly, though the region of transition is indefinite, into the somewhat steeper slopes which rise to the summit plateau. Viewed from the ridge south of this flat, Mauna Loa appears as a distinct mountain until the genetic significance of the long belt of cones is understood (see the photographs, Plate VI, *a* and *b*).

This belt of cones marks an unmistakable major rift zone, which joins at the summit with that leading down the northeast flank of the mountain—a great crust fracture, as a whole slightly curved and convex to the northwest, through the whole dome of Loa. This stretches northward across the flat and bounds on the west that part of it seen on this reconnaissance.

SOURCES OF ERUPTION

As was anticipated, the sources of the eruption of 1916 were found to lie in this major rift zone. Both the sources of earliest outbreak, high on the dome, and the sources of flow lie in it. Both were seen to constitute segments of the rift zone, and to be themselves rift traces in this zone.

THE SOURCE OF EARLIEST OUTBREAK

A long fissure marked by constant emanation of steam (or fumes) was seen leading from near the summit plateau of Mauna Loa down the south-southwest side of the upper slopes of the dome

nearly to the region where this grades into the great flat—a distance of several miles (see the photographs, Plate VI, *a* and *b*). For the most part the steam was clinging to the surface along the line of fissure; but at one point (and possibly a second) it was rising definitely in small volume. Unquestionably this eruption marks a minor rejuvenation in 1916 of the action of rifting through Loa, and in this upper segment were the orifices, large and small, from which came the outrush of fumes in the morning of May 19. The place, or places, where steam appeared to be rising definitely was well up the slope beyond its transition into the flat. The line of fissuring marked by steam emanation possibly is interrupted, and perhaps is offset *en echelon*. This could not be determined positively when seen from so considerable a distance. This fissure leads down in line with the primary system of double semicones which stretch across the flat along the rift zone from near Puu o Keokeo. This line of new steam emanation was seen definitely at all times when the upper slopes were in the field of vision.

THE SOURCE OF FLOW

The source of flow was found to be a freshly opened rift crack or, more precisely, a long, narrow system of closely spaced parallel cracks. This ran in a direction slightly oblique to that of the broad rift zone, but confined well within the limits of it, for some three miles or more, tending very slightly to the west of north from Puu o Keokeo across the flat toward the summit. Its upper limit was not reached on this reconnaissance. Out of these fresh cracks gushed the molten lava which streamed away toward lands in Kona, and toward Kahuku—the streams dividing at the northern base of the group of old cinder cones at Puu o Keokeo. Only the Kahuku branches were seen on this reconnaissance.

OBSERVATIONS NEAR THE SOURCE

Our bivouac for the night of May 30–31 was in the lee of an old triple-peaked, double semicone in the south re-entrant, where its parts straddle an ancient cinder-choked fissure. This cone was elongated in the north-south course of this fissure. It had been the source of an ancient eruption of pahoehoe. This station was

between two and three miles from Puu o Keokeo in a direction a trifle east of north. Just west from here, about a quarter of a mile away, was one of the two larger cinder cones of 1916. This was a double semicone built on either side of the new rift crack. Both north and south of this new cone were several other new cones. A flow of *a–a*, undoubtedly of the date of 1907, separated us from the line of vent of the latest activity.

Though greatly diminished, there was still vigorous action at many points along this line. At first the most active point was a cinder cone near the northeastern base of Puu o Keokeo, between two and three miles almost due south of us (see the photograph, Plate VI, *d*). Though this was down the wind, which was gentle, however, explosive coughing sounds could be heard at frequent irregular intervals; and occasionally red-hot masses were thrown up into our field of vision. This action continued throughout the evening and the early part of the night. During this interval the glow above this vent was considerable, though less than that ordinarily seen above Halemaumau as viewed from the observatory at about the same distance (yet, through the disturbed air, it appeared to be comparable with this). However, at about 8:45 P.M., May 30, a short, sharp earthquake occurred, plainly felt by all three of us sitting or reclining on the cinders in the fissure re-entrant of the old cone. (This shock was felt sharply at Waiohinu and at Kapapala. At Hilea it was felt as the strongest shock of the entire series connected with this eruption.) Within less than a minute, but more than thirty seconds, after this shock there occurred a spasm of greatly increased action at the vent mentioned, with the jetting of lumps of incandescent lava high in the air, and a great increase in the glow. However, the action again quickly subsided to normal. Afterward the action at this vent declined, at first slowly, but toward 1:00 A.M., May 31, more rapidly. By 3:00 A.M. the situation of this vent could barely be made out. When seen again in midafternoon, on May 31, from near Puu o Keokeo, only a smoking cone appeared. There was no revival of activity afterward, so doubtless we witnessed the dying of action at this vent.

In the late afternoon of May 30 a glowing cone was seen, showing an oven-like orifice, situated at a distance of two hundred

to three hundred yards to the northeast of the vent just described. But after night fell the glow above this was negligible.

Between the new cone directly west of our bivouac and the place of greatest activity just described fumes were rising steadily from numerous larger and smaller vents and cones. After darkness came on three of these fuming places exhibited glow. From our viewpoint this glow came and went intermittently, but this appeared to be due to drifting fog and fumes alternately concealing and disclosing the illuminated fume columns.

The larger new cone just west of our bivouac showed steady, vigorous glow on the fumes at both its north and south extremities. These were separated by a dark interval of about 200 feet. No incandescent matter was thrown from this cone into our field of vision.

To the northwest, at a distance of about a third of a mile—hence probably more than $2\frac{1}{2}$ miles from Puu o Keokeo in a direction a little west of north—was a cone which in some respects exhibited the greatest activity of any of the vents, though it was not conspicuous for glow. Indeed, it was remarkable for the comparatively slight amount of illuminated fumes which appeared to spread from it. By daylight this cone was not seen clearly, owing to drifting fog and fumes; but at night it became plainly visible. It was still building. There were numerous incandescent gashes and glow-spots on its sides which remained without substantial change throughout the hours of the night. These were interpreted as true gashes and orifices in the shell of the cone, throngh which shone out the incandescent core. Almost incessantly red-hot masses were thrown out of this cone into the air. Most of these barely cleared the summit to tumble and roll down the sides of the cone. The relative motion of these between and among the practically permanent orifices created the illusion of a steady fountain-play of fiery particles high above the summit of the cone, rising and falling like droplets at the top of a jet of water. It required prolonged observation to correct this impression. At intervals of from twenty seconds to three to five minutes, larger masses were projected into the air high above the apex of the cone. These usually would describe free parabolic curves to fall, apparently, beyond the base of the cone. In most of these cases no rolling was seen. At

the time exaggerated estimates were made of the distance of this cone, and therefore of its height, the height of projection, and the sizes of the projected masses. Drifting fog and fumes gave a greatly lengthened perspective effect. Afterward the cone was visited and found to be distant about one-third of a mile from this bivouac, and to be about 30 feet in height. Whence the height of projection of the molten lumps, at highest, was about 45 feet above the apex of the cone, or 75 feet above its base. No large cinder lumps were found about it. Though the cone was situated across the wind from us, a steady, gentle drift of air, loud, staccato, explosive booms could be heard occasionally accompanying the projection of the larger masses. This cone was the most spectacular remaining center of activity of any which came within our range of vision. On the southwest side of it there was an intermittent illumination of the thin fumes, of a sort which suggested outflow of lava coursing away in the southwest direction. However, the later visit determined that this was a spatter cone higher up the rift than the head of flow, and that any flowing from it was very local and confined within a very small area.

Farther north was seen a glowing orifice like an oven which probably was a gash in a quiet cone. Still a little farther up, rising fumes were seen, but these showed no illumination at night. After darkness fell, nine places altogether were distinguished where rising fumes were illuminated. All of these but one were aligned along the rift crack northward from the chief vent at the northeast base of Puu o Keokeo. The other was the oven, situated a little way to the northeast of this chief vent.

Small quantities of new basaltic pumice, yellow in color, usually in elongate stringers, were found in close proximity to the rift source near its head at the east.

THE KAHUKU BRANCHES

The Kahuku branches of the 1916 flow run in southeast and south-southeast directions from points along the rift source beginning at the base of Puu o Keokeo and extending northward for more than a mile. On our foot journey, on May 30, from 3:00 P.M. on we kept encountering little fuming areas lying to the south of

our route, which indicated the courses of tongues of the new flow. We approached these quite closely as we neared the rift. The trunk of this flow departs from the source at Puu o Keokeo in an east-southeastwardly direction, passing along and around the end of the ridge of ancient pahoehoe that juts out from the cluster of cones; there it swerves to the south-southeastward and spreads down the mountain.

Near the source the lava was pahoehoe in typical surfaces and in broken crusts and fragments. Except near the source the lava in these branches was *a–a* wherever they were approached closely enough for this to be determined. At points on the east these tongues were thin, from 5 to 10 or 20 feet deep; but at the south and along the west the lava blocks were piled irregularly from 20 to 40 feet deep, or high, and were still hot and fuming on May 31.

In passing from the southernmost point to the eastward and northward many thin, narrow tongues (from 5 to 8 or 10 feet in depth, and from 50 to 200 yards in width) were encountered radiating to the southeast and east. These departed from the main stream at higher and higher points. Wherever junctions were seen the departures of these minor branches appeared capricious; that is, no evidences of local damming or pooling were seen. Though thinner and much less massive than the more western streams, these were still fuming, and in varying degrees the air above them was in a state of shimmer from heat. However, the emanation of the fumes furnished a more reliable indication of their courses than the heat-disturbed air above them. (Probably tongues, or "toes," project from the main streams on the western side, as others report who viewed them before they ceased flowing; we found no opportunity to follow the margin closely and did not note any conspicuous projections.)

Any adequate cartographic delineation of the complex outbranching of this Kahuku part of the 1916 flow can be accomplished only by actual topographic survey. (A reconnaissance survey was made in June, 1916, by a party under the Hawaii Territory Survey. An adapted, and in some details corrected, modification of this follows, as Fig. 1. A general conception of a long, narrow,

branching flow (about 5½ miles long) to the southeast and south-southeast, with many minor spreading tongues, is all that could be developed as a result of this reconnaissance.

When we were in the neighborhood of the new lava, smells of subliming sulphur, sulphur acids, charcoal, and cinders were very noticeable. There were also smoke smells from burning vegetation.

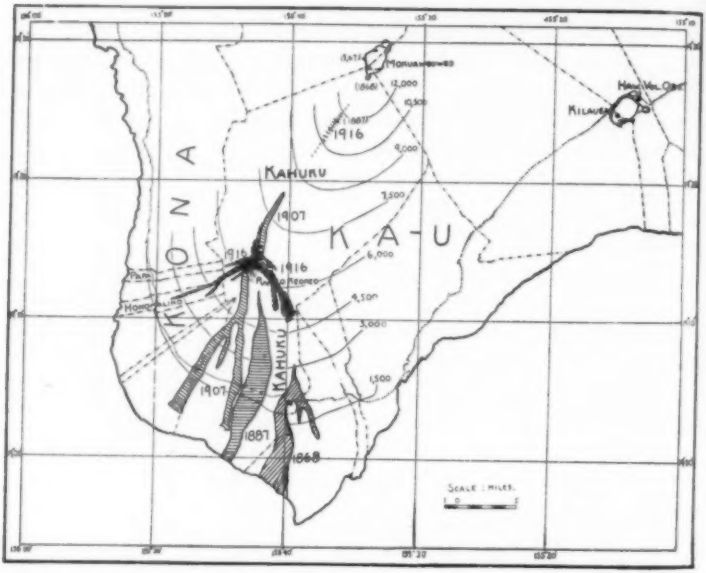


FIG. 1.—A *diagrammatic* map of the 1916 flow and the neighboring region, adapted from a reconnaissance survey by the Hawaii Territory Survey, June, 1916, with corrections and modifications suggested by field work and reports. This plate also shows a *diagrammatic* correction of the course of the 1907 flow near Puu o Keokeo.

IV

The thorough exploration of the region of the source of flow made in company with Dr. A. L. Day in late June and early July served to correct or confirm the findings of the hurried reconnaissance made in the last of May, and to enlarge their scope materially. Also many photographs were made, affording a fairly complete pictorial record of the results of the action at the source. However,

our efforts on this occasion were devoted in large measure to observation of details and to the examination of evidence bearing on the physical-chemical conditions and the mechanisms of flowing in the lava streams near their head. The ideas considered in this connection are best left for future discussion by the writer's companion on this expedition. Here it will suffice to say that much was seen tending to confirm, and some things tending to modify, the writer's conception of the mode of flow of *a–a*, as exemplified by the action observed at the front of the Honomalino branch, described above. Consequently, the space here devoted to this more thorough work is small in proportion to its relative importance.

On June 27, 1916, we set out from the observatory and went by motor to Honomalino, and thence with horses up the southeast flank of Loa to a point in Kahuku, above Papa, at an elevation of about 6,500 feet above sea-level. Here we made camp on barren ground a little above tree-line on this part of the mountain, close beside a short narrow branch of the new flow—the most northwestern of all its definite branches. The six days, June 28—July 3, we spent in exploration of the source region. On July 4 we returned on horseback to Honomalino and by motor to the observatory.

This camp site was situated on the regular, gentle slope of the mountain dome, between $1\frac{1}{2}$ and 2 miles below the junction of this branch of flow with the rift source. Everywhere here the old surface was of ancient, rusty-red pahoehoe and *a–a* commingled in a complicated pattern—except for an area of gray pahoehoe, younger, but still very old, found about $1\frac{1}{4}$ miles above camp. Nearly all our way upward from camp to the source led alongside the new flow over slopes below the limits of the great flat above Puu o Keokeo, but as the 1916 source was closely approached these slopes graded into this upland plain west of the new rift cracks.

The sources of all the branches of the 1916 flow lie in the new rift segment. The 1915 rift here is a newly developed fissure, or in most places a very narrow system of closely spaced fissures (the primary group together nowhere more than 30 feet wide and nearly everywhere much narrower) which extends from the northern base of Puu o Keokeo for a distance estimated closely at $3\frac{1}{2}$ miles in a

direction almost exactly magnetic north[1] (see Plate VI, *a*). This fissure, or system of fissures, is practically uninterrupted and, except for a short curving segment at the north end (see Plate VI, *c*), it follows a straight line. It lies wholly within the limits of the great rift zone, but its course is slightly oblique to the general trend of that, which is about N.N.E. (see Plate VI, *b*), and this suggests a major shear through the mountain. It ends on the north at an old red cinder cone at an elevation of about 7,480 feet above sea-level, while at the south its point of interception with Puu o Keokeo is at an elevation of about 6,600 feet (see maps, Plate I and Fig. 1).

Besides this chief rectilinear fissure, or primary group of fissures, there are a great many secondary cracks, running roughly parallel with the system, especially on the west; on the east there are few. Many of these opened *after* the chief outpouring of lava was over, for they traverse the fresh flows. (It is notable, moreover, that earthquakes continued to increase in number and energy until after the eruption began to decline definitely.) Many, however, traverse the older surface neighboring the source; and here they appear as consistent extended fissures in the more or less solid basalt of the mountain, but also there is noted a tendency for the fissuring to be continued from one crack to another through offsets *en echelon* (see Fig. 2).

Though miniature dislocations have resulted necessarily, there is no observable tendency to any general vertical dislocation; but the repeated evidences of offsets *en echelon* strongly suggest a general horizontal shear. There are, however, no sufficiently well-indicated and extended landmarks, surface features, or structure lines to afford a real test or proof of this. Where these cracks traverse the old surface and where they *cut* the new flow, there generally is no evidence of gas outrush, bulging, or fumarolic action, or any evidence of heat emission.

Altogether, as study progressed the conviction gained force that the amount of rending of the mountain dome here seems out

[1] The general magnetic declination in Hawaii is about N. 10° E., but large local variations make the application of corrections so uncertain that the direct magnetic reading is given here by preference.

of all proportion, either to the outrush of imprisoned gas from this vent (for gas emission throughout the flow was apparently small in volume and relatively very quiet), or to the momentum-pressure of the outpoured magma. Also, the features of the rifting and their distribution appear to differ from those that should be expected to result from such causes. (Resemblances of this action to fissure-eruption phenomena in Iceland are noted below. See especially Plate VI, *c*, and Figs. 2 and 3.) Moreover, as just mentioned, great numbers of weak to moderately strong local earthquakes were registered at the observatory 30–35 miles from the source of action, the energy of these *increasing* even after the cessation of forward movements of the flow, but while the vents at the source

FIG. 2.—A panoramic view looking N.N.E., showing the old red cinder cone riven by new cracks, and the solfatara at the head of the new rift (the figures of the men give scale); and black lava, of 1907, at the base of the cone, which is a little over 100 feet high.

were still freely open. Several of these were felt definitely over a considerable area, having a radius of much more than 30 miles; and one or two of these were quite sharp at the observatory. The question of their origin will be discussed in a later paper.

In brief, for many reasons the conception that this eruption was, in part at any rate, *primarily* a *tectonic* event must be examined thoroughly and not put lightly aside. No very violent action was observed or suggested, nor any such as would be expectable were a rift like this to be produced by explosive forces, or by upthrust from a confined substance tending to expand rapidly or seeking immediate outlet to the surface—as volcanic potential usually is

hypothesized. The lips of the rift were not outforced or uplifted, nor were radial cracks produced. Such action of lava and gas outrush as was observed would be expectable if eruption were *permitted* through tectonic rending of the mountain shell in a manifestly weak zone, thus unsettling the physical-chemical equilibrium of the gas-charged magma afforded exit to the surface and the atmosphere in this way. Many of the eruptions of Mauna Loa have exhibited similar peculiarities, perhaps most of those observed. This whole aspect of eruption here deserves a much more thorough discussion than can be given it in this paper. However, to the mind of the writer, the phenomena of the 1916 eruption appear to illustrate admirably the conception so clearly stated by Geikie,[1] if only the expression "tectonic strain" be substituted for his phrase "terrestrial contraction," with the emphasis in this instance on tectonic strain as a cause.

The fact that some of the circumstances of this eruption might be interpreted adversely to this view may be discussed more advantageously in a systematic study of the seismic accompaniment. Altogether this conception deserves careful attention. Of course, it must not be considered to invalidate or displace views developed from, and applied to, other modes of eruption in other lands, but it must not be rejected simply because it is different from them. Moreover, there is no disposition to overlook the very real application of more commonly recognized modes of eruption in this recent outbreak, or in other eruptions in Hawaii. It is intended merely to give this tectonic mechanism emphasis and to point out its possible, or probable, local predominance.

Lava did not well out of the new rift along its whole length. Hence we may subdivide it, recognizing two segments: a longer flow-source segment, and a shorter solfatara-spatter-cone segment stretching on up the mountain beyond the head of flow.

THE FLOW-SOURCE SEGMENT

For about $2\frac{1}{2}$ miles from Puu o Keokeo in a direction about N. 3° W. mag. the new rift is indicated by a system of open fissures straddled by seven double semicones, varying from 20 to 100 feet

[1] *Ancient Volcanoes of Great Britain*, I, 10–13.

in height and from 50 to 200, or more, feet in the length of the greater diameter, built of pumice, cinders, and spatter outfall—these are also primary sources of flowing streams—with many smaller cones and mouths intervening. The resemblances of these cones and fissures, and their interrelationships, to features in Iceland—especially along the great Laki fissure—as described by Geikie[1] and those from whom he drew, and as exhibited in the views by Anderson reproduced by him, is very striking indeed; few would

FIG. 3.—A view looking north into the gash of the second largest cone of 1916, situated a little south of the head of flow. Its character as a double semicone, built of ejected products, and the channel of outflow from the gash are shown. This cone is about 70 feet high.

question that the course of action was similar in both regions (see the photograph, Fig. 3, especially). Moreover, at practically all points along this segment lava welled out and flowed on both sides of the open rift in southeast, south, or southwest directions down along the course of the fissure system and out along narrow, jutting tongues of greater or less length, as well as down the greater streams. One of these, the largest, led toward Kahuku (see the photograph, Plate VI, *d*), and three others led toward

[1] *Op. cit.*, II, 260–65, Figs. 292, 293.

Kona, two of which were relatively small, though not to be mistaken for tongues. Of all these greater streams the Honomalino branch was longest (see the map, Fig. 1).

At its upper end the area of the new flow is narrow, varying in width up to a third of a mile, and elongate parallel to the rift; its margins here are irregular and lobate on a small scale.

THE SOLFATARA-SPATTER-CONE SEGMENT

For a mile above the head of outflow the open-fissure system continues, at first in a direction about N. 3° W. mag., but in its last third it curves gently eastward, so that the direction from the foot of the flow-source segment to the head of this upper segment is N. 2° W. mag. It is marked by an almost continuous line of fresh solfataric action along which, in numerous protected niches, very delicate, feathery, sulphur crystals were subliming in considerable quantity, apparently in unusually pure aggregates (see the photographs, Plate VI, *b*, *c*). This action, and also all conspicuous fissuring, ended in the flanks of an old red cinder cone, whose summit is about 7,480 feet above sea-level and its base 7,375±, which stood directly in the course of the major rift belt not far from its western margin.

Also there were observed along this segment three new spatter cones, the largest 30 to 40 feet in height, wholly isolated from the area of continuous flow; and several small spatter mouths, one of which was situated very near the upper end of the segment at an altitude of 7,370 feet above sea-level.

Near their head the new flows are thin pahoehoe, either in smooth sheets traversed by rift cracks of *later* origin, or, more commonly, broken and torn crusts of pahoehoe transported and piled into an irregular and confused surface (see the photographs, Plate VI, *d*, and Fig. 4). Near the edges of flow, and the edges of festooned flow channels, rough, *a*–*a*-like textures are seen in all intermediate phases between "pulled" pahoehoe and cindery *a*–*a*. Down their courses the flows become thicker and their surfaces more irregular and fragmented, passing finally, within a mile or two, through slaggy phases, into unmistakable

cindery *a–a*. These flows spread indiscriminately over the various materials of the old surface and near-by areas of the lava of 1907.

At and near the sources the following types of new lava were observed:

a) PRODUCTS OF FLOW

Pahoehoe, which here exhibits various surface textures determined by the interrelationships of different conditions during the progress of flowing, such as the degree of viscosity (dependent in part upon the temperature, the gas content, its state of solution,

FIG. 4.—A view looking southeast, showing the cone at the head of flow, thin, fresh pahoehoe spread over old pahoehoe and *a–a*, and the south terminal of the line of solfataras. This cone is from 15 to 20 feet high.

the amount of the crystalline content, etc.), the mass, and the gradient of the surface, all these influencing the rate and manner of flow and the consequent action of subsurface traction on the crusts.

Textures

Pumiceous texture, a finely vesiculated spongy surface very closely resembling basaltic pumice in color and structure.

Lacy texture, a more coarsely vesiculated spongy surface modified by flow tractions so as to resemble patterns of complicated lacework.

Ordinary textures, comprising surfaces of varying character and degree of vesicularity, and surface vesicle patterns, difficult to illustrate or describe except at great length, but common in all fields of pahoehoe.

"Pulled" texture, seen in incipiency in the lacy texture, but extended to most of the ordinary types wherever, through continued traction, the surface was greatly sheared after it had stiffened or partially set. This gave rise to stippled and bladed surfaces, and to actually fragmented surfaces, so thus, by degrees, it passed over into a slaggy *a–a* texture.

The textures most prevalent in the source region were the pumiceous texture and the "pulled" texture.

Slag, a product of flow made up of rough fragments varying in size and in character from torn and wrapped pahoehoe crusts to cindery *a–a* lumps.

In a general way, here slag was characteristic of the flow channels near the source and of an intermediate region down the flows between the typical pahoehoe and *a–a* stages.

A–a, rough-surfaced block lava, typical of by far the greater part of all the 1916 branches of flow.

b) EJECTED PRODUCTS

Basaltic pumice in three distinguishable varieties which, of course, grade into each other: (1) a very finely vesicled variety of light-yellow color, almost a thread-lace scoria in structure; (2) ordinary yellow to brown basaltic pumice, with fused surfaces, resembling pulled molasses candy; and (3) a more coarsely vesiculated brown to black pumice which grades with the increasing size and the decreasing numbers of vesicles into

Cinder lumps, which, in turn, grade with decreasing vesicularity and increasing density into

Slag lumps, (1) some of which exhibit a surface like obsidian; (2) others a surface like *a–a*.

All these were observed all along the rift and about the spatter cones, but the pumice phases were very abundant near the south

end and around the major cones (see the photograph, Plate VI, *d*), while slag lumps were more characteristically found about the spatter cones and along the northern part of the rift course.

Also there was suggestion that the ejection of slag lumps continued after the action of pumice ejection was over, but no *proof* of this could be elicited.

DISTANT OBSERVATION OF THE UPPER SOURCE

The upper source of the 1916 eruption, where the outbursts of fumes occurred on May 19, has not yet been visited, so far as the writer is aware. This is a place on the great mountain dome very remote from trails, and travel with horses over the barren, untracked lava is both difficult and dangerous. This source lay between 13 and 15 miles from our camp—a distance altogether too great to cover on foot in the short time at our disposal over going so rough as that prevailing within and along the rift belt.

However, this region could be seen plainly through the clear mountain air from the old cone at the head of the lower rift, at a distance of a little over 9 miles. With binoculars magnifying eight diameters some of its characteristics could be made out. It lay within, and was much elongated parallel to, the axis of the major rift zone. It extended from near the edge of the summit plateau down the somewhat steep upper slope nearly to the great flat which lies north of Puu o Keokeo. It appeared to have a moderate breadth, say a quarter of a mile. Fumes were clinging, or slowly rising, along its axis, probably from a system of fissures (see the photographs, Plate VI, *a* and *b*). In two places, apparently not far apart, about two-thirds of the way up its course, definite columns of rising fumes could be made out frequently. On one occasion, in the late forenoon of July 3, one of these columns was estimated to reach upward 500 feet before it spread out and dissipated.

At all times when it was clearly visible the surface of this source area, on both sides of the line of fumes, appeared of very light color, even whitish. It could not be determined whether this was due to the sheen of new pahoehoe, to efflorescence of sulphur or

sulphur salts, or to the escape of fumes in very small quantity from numerous cracks distributed over the area. No other explanations of this light color suggested themselves.

Cones of medium size could be seen within the area. Fumes were rising from them and around them. It is uncertain whether these were new cones, or old cones freshly riven. In general, here, eruption does not take place through old fissures reopened; but exceptions are known. There was no great amount of action at night at this upper source. However, the fuming action in the cleft and on the sides of one of these cones strongly suggested that it was of new origin.

Certain features of older origin, found in the neighborhood of the lower source, claim bare mention here.

Above Puu o Keokeo there is a long, narrow flow of fresh, black *a–a* (with long narrow tongues projecting from it over the great flat to the eastward), which stretches along the eastern margin of the 1916 flow source, and in part lies under the 1916 outflow. This begins much farther up the mountain, in the course of the rift, than the 1916 head. Undoubtedly this is lava of 1907, and it is mapped by Baldwin as of this date (see the map, Plate I). However, on his map it is shown as extending down past Puu o Keokeo on the *east* of that group of cones. Nevertheless, on the writer's short reconnaissance he went on horseback up between the flow of 1887 and the Kahuku branch of 1916 onto the ancient lava ridge that projects uninterruptedly eastward from Puu o Keokeo without crossing this lava stream. Hence it is clear that no part of this flow follows the course past Puu o Keokeo shown on that map. This upper stream did, however, pass down on the *western* side of Puu o Keokeo. While the detailed expression of its course, therefore (and of that of a contributory stream from a source below Puu o Keokeo), must await adequate topographic survey, the writer has *diagrammatically* sketched its course on the west of Puu o Keokeo on the map, Fig. 1, showing these southwestern flows. However, he has not attempted to indicate the long tongues which project southeastwardly over the great flat north of Puu o Keokeo, on account of want of data, and of the cartographic confusion that might result.

The 1916 eruption was of small magnitude compared with earlier action originating near its source. There are accumulations of ancient pumice far greater in depth and spread than that ejected at this time. The older double semicones round about are higher and greater and their gashes and fissure systems on a larger scale.

One such ancient source—whimsically designated in field notes as "the lunar crater" because of a steep and relatively high peak of riven blocks which stood near the center of its large, circular depression, or crater-like area—had been the spring of a lava flood *vast* in proportion to the recent flow. All about this old depression, except for its gap at the south, was a high rampart built of huge cinder blocks piled confusedly, and outward from the top of this a slope built of small cinders and pumice fragments fell away gradually.

Also the cones at Puu o Keokeo point to action of far greater magnitude at the time of their building than recently—greater than any action of historic date on the south flank of the mountain. These cones, however, are only a conspicuous group in the well-marked belt extending from the summit down the slope below them. Though perhaps these are the largest of all, there are others of comparable size, both above and below. The suggestion, therefore, attributed to the late S. E. Bishop, that Puu o Keokeo is a vent distinct from Mauna Loa, but subordinate to it, probably must be dismissed. This point, though a digression, is interesting and important, since it might be considered to bear on the question of the genesis of the 1916 eruption.

In connection with this same point it is worthy of note that the eruptions of 1868 and 1887 (and probably of 1907 also) were preceded by outbreaks of fumes and lava much higher up the mountain than their eventual heads of flow—action similar to that preceding the 1916 flow.

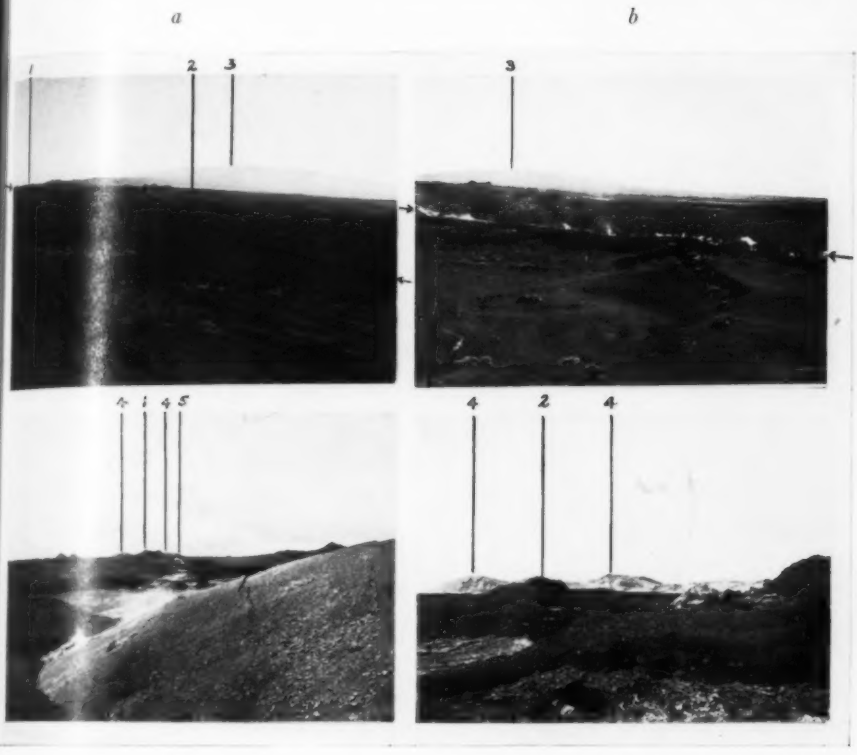
In 1868 such action broke out in the evening of March 26, with a further outburst in the early morning of March 27 "a little to the southwest of the summit," followed by outflow from low sources, at the southwest on Kilauea on April 2, and at the south-southwest on Mauna Loa on April 7. This upper outbreak was very near the summit.

In 1887 the first outbreak was in the evening of January 16 at an elevation of about 11,500 feet on the southwest, and flow began, from a little below Puu o Keokeo, in the evening of January 18.

The exact places of these upper outbreaks were not mapped in either instance.

In 1907, on account of weather conditions adverse for distant seeing, only vague accounts were given. Nevertheless, mention is made, perhaps doubtfully, of an outbreak judged to be at the summit, preceding by a few hours the outbreak of flow lower on the flank.

Hence, though the places of outflow in several of these eruptions have been found suggestively near to Puu o Keokeo, still there is no doubt that the eruptive action in all cases extended far up the south flank of Mauna Loa beyond this group of old cones. Moreover, critical study of the distribution of these heads of flow develops no causal association with this as a center.



a, a view looking a little to the north of east from Puu o Keokeo, showing the flow source. The new rift line, indicated by arrows, traverses the middle ground obliquely. Note the gashed cones; also note the faint streak of fumes, line 3, near the mountain summit, 14–15 miles away—the source of the fume outburst of May 19. Line 1 indicates the larger cone at the chief head of the Honomalino stream. Line 2 indicates the largest 1916 cone at the chief head of the Kahuku branches.

b, a view from an old cone a little N.W. of the head of *flow* looking about N.E. at the northern portion of the new rift, indicated by short arrows at margin, marked by solfataric action. Note also the streak of fumes, and the light-colored area, at the source of the outbreak of May 19, line 3.

c, a view looking south toward Puu o Keokeo from the old cone at the head of the new rift. Note the slight curve in the line marked by solfataric action, with new cones beyond; line 1 indicates one of the larger new cones at the chief head of the Honomalino stream, line 5 indicates the small cone at the head of flow, and the lines 4 indicate Puu o Keokeo, 3½ miles away. In the foreground is a freshly riven spur of the old cone.

d, a view from near the eastern edge of the new flow, looking S.S.W.—a detail of the source near its southern end, showing the cone at the head of the Kahuku branches; line 2, a short tongue of 1916 lava projecting eastward, and old surface in the foreground. A considerable fall of new, basaltic pumice partly covers both old and new lava here. The lines 4 indicate Puu o Keokeo.

A PROPOSED DIP PROTRACTOR

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The device herein described consists of a celluloid chart giving the dip of any plane along a line at any given angle with the strike. Several tables for this purpose have appeared which, for office work, are entirely satisfactory. The protractor has in a certain class of

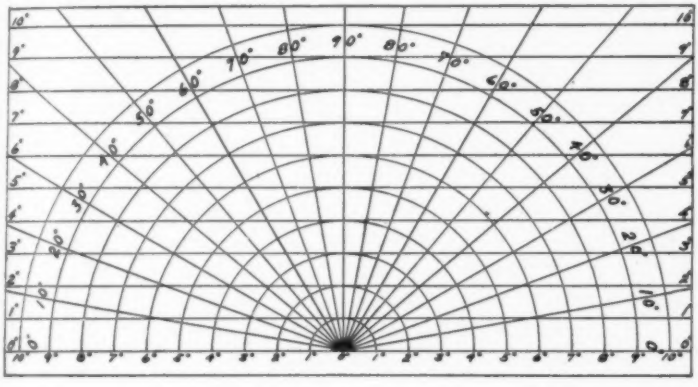

FIG 1.

fieldwork, which will be outlined below, a superiority over the tables and has not, so far as I am aware, been before described.

The protractor consists of a rectangular plate of transparent celluloid ruled and numbered as shown in Fig. 1. The circular curves represent each a given angle of dip of the plane, i.e., the maximum angle commonly denoted dip. The intersection of the appropriate curve with the radiating line of direction of the required dip cuts off an ordinate, or distance from the horizontal

diameter line, the value of which in terms of the vertical scale at the side is the required angle of dip.

As an example, let it be required to find the angle of dip in a direction 40° from the strike, of a plane of which the maximum dip is 5°. Following the 5° curve to its intersection with the 40° radial line and interpolating this point between the 3° and 4° parallel lines we find the value of approximately 3°15′ which is the desired angle of dip.

The particular field of usefulness of this device is in projecting the plane of a given stratum whose dip and strike are known from a plane table set up on the outcrop. We have in this case the dip and strike of the plane and the direction of the line of sight for which we wish the dip. The horizontal diameter line of the protractor is laid parallel to the strike as recorded on the oriented plane-table sheet and the alidade set on the required line of sight with its edge passing through the center on the protractor. At the intersection of the ruler edge with the appropriate dip-curve is read the required angle of elevation or depression to be set on the telescope to project the plane. This graphic solution of the problem in the field and directly on the plane table is much more rapid than a combined protractor and dip-table solution and is sufficiently accurate for reconnaissance and mapping purposes where projecting the outcrop on topography is the "best guess" the field man has in many instances.

The protractor as shown is made only for angles up to 10° because occasions for projecting dip in cases of higher dips are much more rare and correspondingly less accurate, and greater accuracy for the low angles is attained by putting fewer lines on the celluloid. The radii of the several dip circles are constructed proportional to the tangents of the respective dip angles, as is also the spacing of the parallel horizontal lines which are tangent to them. Thus if A is the nominal dip of any plane, B the required oblique dip, and C the angle of obliquity, we have

$$\sin C = \frac{\tan B}{\tan A}$$

and a circular arc may be used for the dip-curve. For the low angles as shown on the protractor in Fig. 1 the tangents are so nearly proportional to the angles that the spacing intervals depart from equality by an inappreciable amount only. There should be no difficulty in reading required dip angles to the nearest two or three minutes of arc with the protractor as shown, and several protractors might provide for the whole range up to ninety degrees for those requiring the higher angles.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

ABENDANON, E. C. *Considérations sur la composition chimique et minéralogique des roches éruptives, leur classification et leur nomenclature.* La Haye, 1913. Pp. 34.

ANDERSEN, OLAF. "The System Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, XXXIX (1915), 407–54.

A description and discussion of experimental methods used, and results obtained, by fusing quartz, alumina, calcium carbonate, and magnesia. Solid phases of anorthite, forsterite, cristobalite, tridymite, clino-enstatite, and spinel were observed, and their thermal and optical properties determined. Anorthite and silica form a simple eutectic system, forsterite and silica form a system with an unstable compound, while anorthite and forsterite form no true binary system. The application of the results to igneous rocks is pointed out.

ARSCHINOW, W. W. *On Inclusions of Anthraxolite (Anthracite) in Igneous Rocks of Crimea.* Petrographical Institute "Lithogaea," Publication No. 4. Moscow, 1914. Pp. 15. (In Russian language.)

The term anthraxolite, originally proposed by Chapman for anthracite found associated with quartz and pyrite in certain veins in the Lake Superior region, is used by Arschinow for all bituminous substances. Such substances occur in the form of small, black inclusions in igneous rocks in two places on the southern shore of the Crimea. Since it also occurs as vein and cavity fillings in the rock, and in many cases is associated with calcite and quartz, it was probably formed, after the cooling of the magma, by the destructive distillation of bituminous substances disseminated in the stratified rocks.

BALL, SYDNEY H., and SHALER, MILLARD K. "Contribution a l'étude géologique de la partie centrale du Congo belge y compris la région du Kasai," *Ann. soc. géol. Belgique*, 1913, 199–247, map 1, pl. 3.

The writers found diabase, granite, diorite-gneiss, granitoid-gneiss, chlorite-schist, and amphibole-gneiss in this region.

BECK, KURT. "Petrographisch-geologische Untersuchung des Salzgebirges an der oberen Aller im Vergleich mit dem Stassfurter und Hannoverschen Lagerstättentypus," *Zeitschr. f. prakt. Geol.*, 1911, pp. 23, figs. 6, pl. 1.

Discusses the sequence of deposition and the characters of certain salt deposits, and compares them with the well-known deposits in Stassfurt and Hannover.

BECK, KURT. "Petrographisch-geologische Untersuchung des Salzgebirges im Werra-Fulda-Gebiet der deutschen Kalisalzlagerstätten," *Zeitschr. f. prakt. Geol.*, XX (1912), 133–58, figs. 12, pls. 2.

Discusses the stratigraphical and structural relationships of the salt deposits of Werra and Fulda.

BEGER, P. J. "Zinnerzpneumatolyse und verwandte Erscheinungen im Kontakthofe des Lausitzer Granits," *Neues Jahrb. Min., Geol., und Pal.*, 1914 (II), 145–82, figs. 4, pls. 2.

The writer discusses the contact zone of the Lausitz granite, describes various pegmatites, greisens, etc., and concludes that the chlorite in the highly metamorphosed greywacke is a pneumatolytic mineral due to the adjacent granite.

BENSON, W. N. "The Geology and Petrology of the Great Serpentine Belt of New South Wales" (in five parts), *Proc. Linnean Soc. New South Wales*, XXXVIII (1913), 490–517, 569–96, 662–724; XL (1915), 121–73, 540–624; maps 6, figs. 29, pls. 10.

The region described in these papers passes north and south through Tamworth, and lies between Sydney and Brisbane, about 280 miles from the former. Through the center of the region extends a north-and-south fault, separating it into two portions. Along this fault is a series of intrusions of rocks now serpentine, not continuous but forming separate patches from 100 yards to 30 miles in length and from a few inches to nearly two miles in width. The formations indicate that after a long period of sedimentation heavy orogenic pressure came from the east, folding and metamorphosing the eastern series, but having less effect on the western. The pressure caused the formation of an overthrust fault which became the channel for the ascent of certain

basic rocks. The sedimentary formations, which prior to the folding had a thickness of over 30,000 feet, are described, and a list is given of the fossils found.

The igneous history begins in Lower Devonian times with the extrusion of spilitic lavas and tuffs. In the Middle Devonian similar rocks attain a thickness of over 7,000 feet, and associated with them are 2,000 to 3,000 feet of intrusive dolerite, in many cases albitized. In Upper Devonian times some 3,000 feet of agglomerates were formed, and, after a long period of quiet, rhyolites, andesites, and tuffs appeared in the Lower Carboniferous. The intrusion of the peridotites then followed, chiefly along the fault line previously mentioned, and probably during the crust-movement at the close of the Carboniferous. Gabbros and eucrites came later than the serpentine, and cutting these are dikes of dolerite. From latest Carboniferous to early Mesozoic times came a long series of granitic intrusions consisting of granodiorites and porphyries, and titanite-, tourmaline-, and other granites. Besides these rocks there are numerous lamprophyres whose time period was not determined. Following the Permo-Carboniferous was an era of great crumpling, then followed a long period of erosion which exposed the granite, and then a later period of sedimentation. During Tertiary times the formations were largely volcanic, and thick flows of basalt occurred. A great period of elevation and block-faulting closed the Tertiary.

The second paper deals with the geology of the Nundle District, and the third with the petrology of the entire region. Various rocks are described: spilites, used in the sense of Dewey and Flett for lavas with sodic feldspars, contain acid oligoclase and augite with some secondary chlorite and epidote and with or without magnetite; the so-called "keratophyres" are composed almost entirely of acid oligoclase with some interstitial chlorite from augite; the dolerites consist of plagioclase (andesine to albite), augite, magnetite, with a little quartz and various accessories, and are medium-grained. The term dolerite is apparently used in a different sense from that common in the United States, where it signifies a coarse-grained basalt containing a basic plagioclase. The writer speaks of albitization proceeding inward in the feldspars, by which he means, apparently, that the sodic rims are secondary. It would seem more probable that the zonal rims are primary. The rock thus appears to be an augite-andesite. The peridotites are chiefly harzburgites, but there are local occurrences of dunite and lherzolite. With the absence of olivine, enstatolites occur. Associated with the

peridotites and pyroxenites are rarely amphibolites and olivine-gabbros, more commonly eucrites and anorthosites. The silicic rocks described are felsites, granodiorites, and various granites. Malchites, granite-porphyries and quartz-porphyries, and minettes, vogesites, and camptonites occur as dikes.

Twenty-two analyses are given of rocks of this region, unfortunately showing a number of typographical errors and errors in proof-reading owing to the absence of the author from the state during the passage of the paper through the press.

The fourth paper deals with the dolerites, spilites, and keratophyres of the Nundle District. In this the statement is made that the feldspar of the keratophyre is pure albite and not acid oligoclase, as stated in the earlier paper. The spilites, dolerites, and keratophyres all appear to be intrusives in the sediments. Certain of the spilites, in the opinion of the author, were intruded into soft mud, for they show a pillow structure. Most of the rocks are rich in primary albite.

The fifth paper is on the geology of the Tamworth District. A series of radiolarian claystones was deposited at shallow depths on a steadily sinking sea-floor in Devonian times. There were two periods of volcanic activity, and masses of tuffs and agglomerates accumulated in the sea, and spilites, dolerites, and keratophyres were intruded. The total thickness of the series is unknown, but apparently about 12,000 feet are Middle and Upper Devonian. Faulting and folding took place in the Carboniferous period, followed by peridotitic intrusions, and later by intrusions of granite. A final eruption of basalt occurred in the Tertiary period.

BERKEY, CHARLES P. "Petrographic Range of Road-Building Materials," *School of Mines Quart.*, XXXV (1913), No. 1, pp. 6.

BLANCHARD, RALPH C. *The Geology of the Western Buckskin Mountains.* Dissertation. Columbia Univ., 1913. Pp. 80, numerous figs.

BOEKE, H. E. "Bemerkung über die Theorie von J. Johnston bezüglich des Verhaltens fester Stoffe unter ungleichförmigem Druck," *Centralbl. f. Min., Geol., u. Pal.*, 1913, 321–24.

BOEKE, H. E. "Die Methoden zur Untersuchung des molekular Zustandes von Silikatschmelzen," *Neues Jahrb. Min., Geol., u. Pal., B.B.*, XXXIX (1914), 64–78.

BOEKE, H. E. *Grundlagen der physikalisch-chemischen Petrographie.* Gebrüder Borntraeger, Berlin, 1915. Pp. xii+428, figs. 168, pls. 2.

In view of the important bearing of recent physico-chemical research upon the problems of the origin of igneous rocks, this work is most timely and acceptable, and is to be recommended to all advanced students of petrology. It is an invaluable summary of work already done, and contains many suggestions for future work.

The author not only presents the results of previous work but describes in detail the methods and apparatus by which these results were obtained. The subject is presented in a very clear and orderly manner, and as simply as is compatible with the nature of the subject. In his treatment the author follows the inductive or synthetic method, that is, he describes first the behavior of the simplest constituents of rocks under known conditions of composition, temperature, pressure, time, etc., and compares the results with those found in nature. Beginning with the magma, he traces it through all stages of cooling and through the gradual changes which take place in its solidification products.

In older petrologic textbooks there is a great variety of views as to observed phenomena, primarily because so many factors must be taken into consideration, and one or another may predominate. Since in many cases there are more unknown than known factors, a single solution may be impossible. The synthetic method seeks to determine, by exact and systematic investigation, the action of each factor, such as temperature, pressure, capillarity, etc.

In most provinces of petrology only the beginning of inductive research has been made, and the experimental work so far is no more than a groping after the truth. Little can be said at the present time as to the formation of rocks from their complicated magmas, and physical chemistry can not yet settle such questions as the origin of magmatic differentiation, the relation between the alkali and alkali-lime rocks, and that of dike satellites to parent rock, etc., on account of the lack of reliable data.

The present text is so comprehensive that only the very briefest outline of the contents of the various chapters can be given; a list of the

subheads alone would require five or six pages of this Journal. After a short discussion of homogeneous and heterogeneous equilibria, the subject of magmatic rock-formation is taken up. Under this head the author treats of the essential components of magmas and the melting-points of minerals, and includes a discussion of various methods of determining melting-points and of obtaining and measuring high temperatures in the laboratory. He speaks of the alteration of melting-points at different pressures, of uniform and non-uniform pressures, and of overheating and undercooling. Under the properties of silicate melts are included internal friction and diffusion, surface-tension, electrical conductivity, influence of gravity and centrifugal force upon the composition of melts, measurements of density at high temperatures, etc. Following a chapter on the inversion points of minerals, he discusses the genetic significance of melting- and inversion-points in rock-forming minerals. He describes two, three, four, etc., point systems, and then devotes about seventy-five pages to the physico-chemical, especially the thermal, properties of the more important rock-forming minerals.

In the second division of the book the author takes up the gases in magmas—their nature, their solubility in melts, and their equilibrium. In the third division he treats of the pegmatitic, pyrohydatogenic, and hydrothermal phases of the solidification of magmas. Here are included the properties of water at high temperatures, and a general discussion of the formation of minerals in systems with volatile components. Then follows a chapter on the synthesis of pneumatolitic and hydatogenic minerals; then hydrothermal synthesis, solubility of the common products of hydrothermal mineral-formations, alteration with temperature and pressure of salts which are but slightly soluble, the relationship of solubility and size of grain, succession and paragenesis of the hydrothermal ores and vein-minerals, zeolites, etc.

The fourth division is devoted to weathering or colloid mineralogy; the fifth to sediments. Here is included a long discussion of salt deposits (43 pp.) to which the author has devoted considerable study. The book closes with a short chapter on metamorphism and a double column index of 26 pages.

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